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SOME RED TIDE CHARACTERISTICS DURING 1952-1954

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ABSTRACT

Survey counts of *Gymnodinium brevis*, miscellaneous chemical analyses (Kjeldahl nitrogen, total phosphorus, total organic matter, chlorophyll, and nitrate), and a few light intensity and productivity measurements in Florida's red tide zone from 1952 to 1954 indicated a widespread general regime of this dinoflagellate growing sparsely in heterogeneous poor to moderately fertile water with a high N/P ratio. Occasional bloom patches and fish kills were accompanied by somewhat higher nutrient levels. The fertile estuaries, Tampa Bay and Charlotte Harbor, in contrast to the Caloosahatchee River are capable of stimulating coastal fertility with injections of nitrogen and phosphorus. Offshore mixing of high N/P ratio water of the Caloosahatchee estuary and the low N/P ratio water of Tampa Bay and Charlotte Harbor may produce a wide range of nutrient conditions. A decrease in estuarine pollution is suggested as a remedial experiment.

INTRODUCTION

In this report some accumulated data are presented on marine and estuarine waters during and between red tide outbreaks in Florida, 1952 to 1954. These data help further to establish some characteristics of natural red tide blooms of *G. brevis* and complement other published studies.

During most of the period of study the waters of the red tide zone (a 150 mile zone of coastal water from Clearwater to Naples, Fla. from the coast out to 50 miles with salinity of about 33 parts

[1]Data accumulated at the University of Florida as part of the University Red Tide Project, J. B. Lackey, leader. N. Marshall contributed from the Oceanographic Institute, Florida State University.

per thousand) chronically and continuously contained the red tide organisms, usually in small concentrations not thought to be lethal to fish. Then, at frequent intervals, intense temporary and localized redwater blooms occurred in patches with accompanying fish kills reported. At present considerable uncertainty (Ryther, in press; Ingle and de Sylva, 1955; Odum, 1953) exists as to the factors responsible for this regime, which contrasts with years between 1950 and 1952 when no *Gymnodinium brevis* could be found in the area even with extensive searching by the U. S. Fish and Wildlife Service. No attempt is made to review all contrasting evidences in this short communication, but some definite assertions are made as to some characteristics of the recent red tide phenomena.

Methods

Kjeldahl nitrogen determinations were made by Odum and Hynes on 800 to 1000 cc samples following Robinson and Wirth (1934).

Total phosphorus determinations were made by Odum and Hynes by Deniges colorimetric method after acid digestion following Robinson and Kemmerer (1930).

Determinations of total organic matter were made by Odum and Hynes with the alkaline permanganate oxidation method of Benson and Hicks (1931).

Nitrate nitrogen determinations were made by Odum with the strychnidine method of Zwicker and Robinson (1944).

Light measurements were made by Odum and Lackey with a submarine photometer containing a Weston cell No. 594YR with visible spectral sensitivity. Readings at 3 foot intervals were obtained. and extinction coefficients were computed below 3 ft. (Sverdrup *et al.*, 1946).

Water samples for cell counts by Lackey were preserved in the field with 5% formalin and centrifuged.

Chlorophyll determinations by Marshall were made by filtering water samples through barium sulfate coated Whatman No. 42 filter paper and extracting the filtered material in 90% methyl alcohol. Extracts were read in a Klett-Summerson colorimeter and interpreted by comparison with acetone extracts read according to the method of Richards and Thompson (1952).

Production measurements were made by Odum with B.O.D. bottles covered and exposed to light.

Reproducibility (plus and minus confidence limit) for the rough

chemical methods used is estimated as follows: total phosphorus, 20%; Kjeldahl nitrogen, 30%; organic matter, 50%; nitrate nitrogen, 25%; chlorophyll, 20%.

Patterns of Distribution of G. brevis

Routine sampling and counting of *G. brevis* in water of the red tide zone during this period have indicated the following:

(a) No noticeable discoloration of the water was evident for surface blooms of 200 cells/cc such as off Sanibel Island on March 5, 1954; slight coppery color was observed in bright sunlight when there were 800 cells/cc such as in one patch on April 30, 1954.

(b) Judging from field correlation, about 450 cells/cc are required before quick fish kills are reported. The University of Miami workers (Smith *et al.*, 1955) reported a mild fish kill with a field correlation of 80 cells/cc. However, this does not prove that water with these cell counts is always lethal. Some small shore fishes placed in water with 800 cells/cc April 29, 1954 off Englewood did not show distress.

(c) On many occasions such as on August 12, 1954 in daytime off Sarasota Point many more *G. brevis* were found on the bottom than at the surface. The swarming of *G. brevis* to the surface commonly observed where high concentrations are present in stationary flasks of water has not been observed in the daytime field sampling although no really high counts (over 10,000/cc) were encountered. Vertical migrations by dinoflagellates up at night and down in daytime are well documented (Hasle, 1950). Vertical counts at night are needed.

(d) *G. brevis* in concentrations of 393 cells/cc have been found by us as far out to sea as 12 miles, 49 cells/cc 20 miles offshore and 2 to 5 cells/cc 100 miles offshore (Dec. 30, 1954) during the red tide regime.

(e) *G. brevis* has been found in estuaries in salinities as low as 19.1 PPT as on July 23, 1954 at the mouth of Gottfried Creek.

(f) Sampling at times failed to reveal *G. brevis*. For example, samples showed no *G. brevis* between October 16, 1953 and December 18, 1953 at Clearwater; between December 2, 1952 and September 1, 1953 at Naples; and between October and December, 1954 at Naples. Since curves relating number of species and the quantity of environment sampled rarely flatten (Rice and Kelting, 1955), it is not possible to prove that larger samples would not have revealed individual *G. brevis*.

(g) Local swarms of other dinoflagellates: *Gymnodinium splendens* and *Prorocentrum triangulatum* aroused no local comment.

These counts are in general agreement with 1954 data collected by Smith *et al.* (1954).

Characteristics of Coastal Water With G. brevis But Between Intense Bloom Periods

Data of several kinds below indicate that the water in which the red tide organisms occur in inter-bloom periods is high salinity water that is relatively impoverished of nutrients at times and moderately fertile for a coastal water at other times.

A very detailed picture of the distribution of phosphorus has been

TABLE 1
Nutrient Characteristics of the Red Tide
(The number of values averaged to obtain mean values are given in parentheses.)

	Salinity PPT	*G. brevis* cells/cc	Kjeldahl Nitrogen mg-atom/M^3	Total Phosphorus mg-atom/M^3	N/P
ESTUARINE NUTRIENT SOURCES (1952-1954)					
Tampa Bay	19. --30.	0	38. (4)	14. (8)	2.7
Peace Rive Estuary	.2--20.	0	24. (3)	19. (6)	1.3
Caloosahatchee Estuary	.2-- 1.	0	23. (4)	1.1 (6)	21.
Coastal Artesian Water*	.2-- 1.	0	7. (2)*	.4 (2)*	18.
COASTAL WATER CONTAINING *G. BREVIS*					
4 miles off Sanibel Island, November 16, 1952, Red Water	35.	---	58. (1)	2.5 (1)	23
Sarasota, coastal water, September 3-4, 1953	---	3-1732	---	.44(7)	--
Bradenton Beach, 1 to 10 miles offshore, September 18, 1953	---	0-2444	13. (4)	---	--
1 to 14 miles offshore Sanibel Island, March 6, 18, 1954	33. --35.	18-393	6. (9)	.44(6)	14
Englewood and Sarasota, June 18, 19, 1954	33. --35.	300-4814	19. (16)	<.5 (18)	>38
Englewood and Sarasota, July 23, 30, 1954	33. --35.	0-710	18. (7)	<.5 (21)	>36
Sarasota, coastal water, 1-24 miles offshore, August 11, 12, 1954	35. --37.	0-146	13. (15)	.51(17)	26

*NO_3-N and PO_4-P; Weekiwachee Springs and Homosassa Springs.

emerging from the extensive analyses published (Smith *et al.,* 1955; Graham, Amison, and Marvin, 1954; Odum, 1953). Since almost no study of the nitrogen sources has been made, a series of Kjeldahl determinations were made as reported in Table 1.

Most of the nitrogen offshore is in organic form. Fourteen nitrate-nitrogen determinations made in the field October 6, 1953 gave values all less than 2 mg-atom/M^3 in non-red water containing about 40 cells/cc *G. brevis* and dead fish 2 miles west of St. Petersburg, Fla. (Dead fish may persist after blooms and may be carried away from such patches into non-bloom water.) On an overcast day March 6, 1954, 2 miles off Sanibel Island, nitrate-nitrogen levels were between one and 3 mg-atom/M^3 compared to 4 to 16 mg-atom/M^3 Kjeldahl nitrogen associated with 100 cells/cc *G. brevis.*

The levels of phosphorus and nitrogen in Table 1 from September, 1953 to August, 1954 are fairly low suggesting infertile water offshore. Very low phosphorus levels were found offshore from 1950-1952 by Graham, Amison, and Marvin (1954). Thus, the general phosphorus levels of these coastal waters seem similar in a red tide year to those in a non-red tide year.

Analyses made of total organic matter revealed 3.0 ppm (oxygen consumed) at Cedar Keys, Fla. north of the red tide zone, but only 1.0 ppm total organic matter was found in inter-bloom water off Englewood, April 29, 1954. Values of 1.0 ppm in tropical waters, 2.0 ppm for the open sea, and 7.0 ppm for inshore waters have been found elsewhere with this method (Sverdrup *et al.,* 1946). Thus, a relatively poor water is indicated.

Further idea of the water character is gained from some rough light measurements below 3 ft. Extinction coefficients per meter of .20 to .27 were found on April 30, 1954 for the band of visible wavelengths measured. This was of a magnitude that is low for coastal waters (Sverdrup *et al.*, 1946). One of these measurements was made through a brown water patch with 800 cells/cc *G. brevis.* Intense light thus prevails in these shallow, red tide zones which are only 10 to 40 ft. deep. Thus, on this date 40 to 50% of light in the visible range reached 9 feet in a near-bloom patch and in inter-bloom water. If 10,000 ft.-candles full sunlight strikes the sea surface, 4000 or more ft.-candles illumination reaches 9 feet. 8% or 800 ft.-candles penetrates to 40 ft. (Experimental culture of *G. brevis* by Wilson and Collier (1955) was done at lower light intensities of 175-300 ft.-candles). Measurements on March 6 indicated a

much more turbid condition more characteristic of coastal waters with an extinction coefficient of .39. When the large number of Secchi disc readings (D) of Smith *et al.* (1955) are converted into extinction coefficients (K) using the approximate relation $K = 1.7/D$ (Sverdrup *et al.*), a range of values similar to these results.

Two production experiments were attempted with water containing *G. brevis*. In the first experiment[2], with water off Sanibel Island, March 7, 1954, a moderately high figure of .045 mg oxygen/liter/hr. was obtained. In the second experiment[3], with water off Englewood, April 29, 1954, a low value of .006 mg oxygen/liter/hr. was obtained that was probably not significantly different from zero. Thus, values as low as Dry Tortugas and as high as Long Island Sound (Riley, 1949) were obtained in the same area indicating large shifts in basic conditions.

Characteristics of Bloom Patches

It now seems clear that although occasional bloom patches have extreme concentrations of nutrients (Ketchum and Keen, 1948) the usual blooms capable of killing fish are of lesser magnitude and are accompanied by only a slight increase in total nitrogen and phosphorus. Note the moderately low nutrient levels associated with the higher counts of *G. brevis* reported in Table 1. Although numerous, the biomass of these tiny cells is not large. A computation below similar to one by Ryther (in press) shows that fish killing blooms need not have excessive nutrients.

Suppose that water with 1000 cells/cc *G. brevis* is toxic to fish. Let us assume: 90% water, a density of one, 4.5% nitrogen in dry dinoflagellates (Vinogradov, 1953), and dimensions of one *G. brevis* cell of 25, 13, and 31 microns (Davis, 1948). There is thus only 3.2 mg-atom/M^3 nitrogen in populations with a concentration of 1000 cells/cc. Thus, it is the intense toxicity of the red water that makes the otherwise ordinary growths of importance. The highest cell concentrations reported in extreme blooms (Davis, 1948) are about 15 times this figure. The usual bloom of lesser intensity may

[2]Experiment No. 1, March 7, 1954, water collected 2 miles south of Sanibel Island, sky overcast, stratocumulus clouds, light source used: fluorescent lights in laboratory, duration of experiment 8 hrs. Mean of 5 dark bottles at completion 6.83 mg/1. oxygen (Winkler). Mean of 5 light bottles at completion 7.19 mg/1; 312 cells/cc *G. brevis* present at start. [3]Experiment No. 2, April 29, 1954, 5 miles off Englewood, Fla., 1/10 cumulus cloud cover, light source: mid-day sun on boat deck, time of measurement 5.25 hours, bottles on deck kept cool with padded newspaper and frequent drenchings. Mean of 3 dark bottles at completion 6.65 mg/1. Oxygen mean of 3 light bottles at completion 6.68 mg/1.; 66 cells/cc *G. brevis* present at the start.

require only small injections of nutrients to achieve toxic surges in impoverished inter-bloom water already containing sparse populations of *G. brevis*. Additional concentrating mechanisms are required for the extreme cases. For example, Ketchum and Keen (1948) suggested concentration by vertical migration of the organisms.

Chlorophyll determinations in the November, 1952 outbreak demonstrate clearly the extremely local nature of the patches of red water that occur in a bloom. 30.7 mg/M^3 chlorophyll was found 4 miles west of Sanibel Island in a red patch whereas only 5.9 and 6.5 mg/M^3 were found a few yards away in clear water. Water that was recognizably red in a patch 12 miles offshore nevertheless had only 5.1 and 14.3 mg/M^3 chlorophyll suggesting that only the heaviest blooms of *G. brevis* really contain appreciable protoplasmic biomass that would require large nutrient concentrations. To be considered in comparison are mean values from Riley (1938, 1941a, 1941b): .33 mg/M^3 chlorophyll in impoverished water at Dry Tortugas, Fla., 5.68 mg/M^3 in moderately fertile water on Georges bank, and 17.44 mg/M^3 for fertile Long Island Sound. These data are discussed further elsewhere (Marshall, in press).

Characteristics of Estuarine Nutrient Sources

The continued localization of the *G. brevis* phenomenon in the same area of the southwestern coast of Florida continues to imply that important inorganic or organic nutrient conditions are being supplied from estuarine sources or being conserved in coastal water in the area. There are three main estuaries: Tampa Bay with a mean discharge of 1136 cubic ft./sec. (Olson, 1953); Charlotte Harbor with 1345 cubic ft./sec. being contributed from the Peace and Myakka Rivers (Phelps and Barry, 1950); and the Caloosahatchee River discharging Lake Okeechobee with widely varying discharges up to 10,000 cubic ft./sec. sustained prior to the hurricane season of some years as regulated by the U. S. Army Engineers.

As discovered and discussed earlier (Smith, 1949; Graham, Amison and Marvin, 1954; Odum, 1953; Smith *et al.*, 1955) and further confirmed here, Tampa Bay and Charlotte Harbor maintain very high dissolved phosphorus levels. This supply comes initially from a natural high content in rivers draining phosphatic rocks, addition of industrial phosphatic wastes from several aspects of mining and processing, and extensive sewage contributions, especially from Tampa, St. Petersburg, and towns on the Peace River (Odum, 1953).

Phelps and Barry (1950) list the following lbs. B.O.D. discharged per day in sewage: St. Petersburg into Tampa Bay, 6,800 (summer) to 25,000 (winter); and Tampa into Tampa Bay, 18,000. Specht (1950) found 8,110 lbs. B.O.D. per day coming downstream from the upper Peace River at Ft. Meade.

Table 1 includes data on the three main estuarine nutrient sources and the ground water. In contrast to the first two estuaries, water discharged through the Caloosahatchee River is fairly low in nitrogen and especially low in phosphorus. Thus, the volume of fresh water here is large, but the concentrations of the nutrients measured are low. The sub-surface ground water discharged directly into the sea probably contains relatively little nitrogen and phosphorus as indicated by analyses of water from Homosassa and Weekiwachee Springs in Table 1. The volume of the sub-surface discharge is unknown.

Olson (1953) has shown that the fresh waters entering Tampa Bay take 2-3 years to accumulate a volume equal to that of the bay and thus to complete a turnover. The flushing action of tidal exchange is faster but possibly because of the cross current phenomenon outlined by Riley and Conover (in press), nutrients are not rapidly lost with tidal outflow, the nutrients from the surface outgoing water being sedimented and carried down into incoming bottom water. Thus, nutrient contributions from the land and pollutions may build up to much higher concentrations in estuaries than would be figured if there were continual dilution in the open sea.

Two of the nutrient laden estuaries, Tampa Bay and Charlotte Harbor, provide a source for discrete masses of fairly rich high salinity water to eddy into the relatively calm shallow coastal water on the surface but with sufficient charge of inorganic and organic nutrients to locally stimulate the impoverished red tide organisms widely dispersed in the coastal water. This is one hypothesis that may help to account for most nutrient levels offshore but not for the occasional very high nutrient concentrations (Ketchum and Keen, 1948) where other concentrating mechanisms may be in operation.

As given in Table 1, Tampa Bay and Charlotte Harbor (the Peace River Estuary) have 14 to 38 mg-atom/M^3 nitrogen and phosphorus in their relatively high salinity zones (half sea water) so that coastal water concentrations of 4. to 20 mg-atom/M^3 could readily result from a one to fourfold dilution. In contrast the Caloosahatchee and ground water with low nutrient concentrations even before dilution would tend to lower the nutrient concentrations when diluted into the

coastal water. That the coastal water off Sanibel Island maintains nutrient levels slightly above that in the open Gulf may be due to conservation of nutrients by some mechanism such as in circulating eddies, conservation mechanisms in an offshore cross current system mentioned above, injections from the two more fertile estuaries further north, or nitrogen fixation.

On September 27, 1952 prior to the red tide outbreak of November, 1952, the high salinity water (32—34 PPT) in the mouth of Tampa Bay contained 8.8 to 10.0 mg/M^3 chlorophyll and 3. to 6. mg-atom/M^3 phosphorus. This water condition representative of the result of mixing of Tampa Bay with coastal water at that time is a good example of the kind of fertile injections that are received by coastal waters of the red tide zone.

Nitrogen-Phosphorus Ratio

The very high phosphorus values of Tampa Bay and Charlotte Harbor cause these waters to possess a very low N/P ratio, far below the utilization ratio of most marine organisms. Thus, inside these two bays phosphorus is not likely to be limiting. In contrast the coastal water and the Caloosahatchee River water have a high N/P ratio. These relatively poor waters might be much fertilized by phosphorus injections from the two first named estuaries in the course of the northward coastal drift (Pierce, 1951).

Since a relatively low phosphorus requirement for culturing *G. brevis* was reported by Wilson and Collier at the Gainesville meeting of the American Society of Limnology and Oceanography, and since relatively low phosphorus concentrations were found associated with most of the recent moderate blooms, doubts have arisen as to whether phosphorus is a limiting nutrient to this organism. Yet the coastal water off much of the coast apparently sustained *G. brevis* continually during 1953-54 with a relatively high N/P ratio above the value of 16 often representative of oceanic waters and plankton nutrient requirements. The high N/P ratios of this impoverished water suggest that either P is the more limiting of the two or that the *G. brevis* can grow with a high N/P utilization ratio. Also the most distinct outbreaks of red tide are correlated with large annual rainfalls in the phosphate districts drained by the Peace River (Ingle and de Sylva, 1955). Thus, it does not seem possible yet to rule out phosphorus as a controlling nutrient of red tide blooms. If phosphorus is not directly limiting it cannot be eliminated from suspicion as a

causal agent since it may be required in larger quantity for the growth of some organism producing a necessary organic requirement for *G. brevis*.

The large difference between the N/P ratio in Charlotte Harbor and Tampa Bay in contrast to the red tide zone outside the bays is similar to a pollution situation in Moriches Bay, Long Island, N. Y. (Ryther, 1954). In Moriches Bay, however, the troublesome bloom being studied was a tiny green alga in the rich bay water rather than a dinoflagellate in poor offshore water. However, unpublished data of Lackey indicates blooms of *Prorocentrum triangulatum* (4000 cells/cc) in the vicinity of duck farms on Moriches Bay.

There is a possibility that the increasing multiple pollution of the shallow coastal estuaries and land drainage cited above may be producing a higher incidence of the red tide phenomenon than might otherwise occur. Authorities responsible for control of this pollution should be made aware of this possibility. In addition to other incentives, pollution control programs might be recommended as an experiment to check the red tide with the realization that a several year lag is to be expected in the effect of this action on the nutrient levels in the polluted bays.[4]

Acknowledgment

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[4]Other remedial suggestions are being considered. The U. S. Fish and Wildlife Service has made large scale experiments with copper sulfate. Odum and Hynes (American Society of Limnology and Oceanography Meeting, 1954, Gainesville, Fla.) suggested the large scale dusting of charcoal as a possible means of adsorbing required vitamins and thus modifying the nature of offshore blooms.

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A FURTHER STUDY OF THE POLYCLAD FLATWORMS OF THE WEST INDIAN REGION

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ABSTRACT

Records and notes of common species found at Jamaica and in the Gulf of Mexico and descriptions of *Pseudoceros texanus* and *Prostheceraeus zebra*.

INTRODUCTION

By West Indian region is meant the central western Atlantic from the Carolinas to southern Brazil, including the Gulf of Mexico, the Caribbean and all its islands, and the Bermudas. This area undoubtedly constitutes a faunal unit (Ekman, 1953) although as regards the polyclads scarcely any species has so far been found in common between the West Indian islands and the coast of Brazil. The discocelid genus *Adenoplana,* however, has not been found elsewhere than in the West Indies and Brazil. Several species of polyclads are spread throughout the Caribbean and the Gulf of Mexico and some of these extend to the Bermudas (Hyman, 1955).

The present article is a further contribution to our knowledge of the polyclad fauna of the West Indian region. It is based chiefly on material obtained during a stay in Jamaica in February, 1955. I am indebted to Dr. Norman Millott for facilities in the zoology building of the University College of the West Indies and to Drs. Jessie Rankin, Peter Bellinger, and Thomas Goreau of that institution for assistance in collecting.

Taxonomic categories in polyclads were defined in two recent articles (Hyman, 1953, 1955) and hence definitions will be limited here to families not encountered in those studies.

Order POLYCLADIDA
Suborder *ACOTYLEA*
Section *Craspedommata*
Family CRYPTOCELIDAE

Phaenocelis purpurea (Schmarda), 1859

Leptoplana purpurea Schmarda, 1859
Phaenocelis purpurea Stummer-Traunfels, 1933
Comprostatum insularis Hyman, 1944

Some specimens of this species were obtained in the first culvert on the Palisadoes Road to Port Royal at Kingston, Jamaica. There are two adjacent culverts that connect Kingston Harbor with a large lagoon and presumably were left as communications between the two, formerly widely connected, bodies of water when the road was built. These two culverts have a good marine fauna and are favorite collecting places for Jamaican zoologists. *Phaenocelis purpurea* is white but often flushed with purplish rose, probably from the eating of some favorite food item. One specimen taken was deeply colored with the tint mentioned but had lost much of the color by the following day. In another specimen the purplish rose tint was limited to the middorsal region. Jamaica is the type locality for this species which has since been found only in the Florida Keys (Hyman, 1944).

Section *Schematommata*
Family LEPTOPLANIDAE
Notoplana ferruginea (Schmarda), 1859

Figure 1

Polycelis ferruginea Schmarda, 1859
Discocelis binoculata Verrill, 1901
Notoplana bahamensis Bock, 1913
Notoplana ferruginea Stummer-Traunfels, 1933
Notoplana caribbeana Hyman, 1939

This is probably the most common polyclad of the Caribbean and its islands but has not yet been taken on the coast of Florida or in the Gulf of Mexico. As shown by the synonymy the species has appeared under a variety of names and probably in fact shows some geographical variation within its range. Jamaica is the type locality and specimens were found in the second of the two culverts mentioned above, further under stones along the sea wall at Port Henderson. In my 1955 article I remarked on the apparent scantiness of the cerebral eyes of the original Jamaican specimen of Schmarda (reinvestigated by Stummer-Traunfels, 1933) and wondered if this feature is constant for Jamaica. I therefore present a figure of the eye pattern of one of the Jamaican specimens secured (Fig. 1). On comparing this with other published figures of the eye pattern of *Notoplana ferruginea* from other localities one gets the impression of fewer cerebral eyes in Jamaican material. In all the published figures, also, one cerebral eye cluster contains fewer eyes than the other. This species is white but a slight buffy tinge appeared middorsally on some of the Jamaican material.

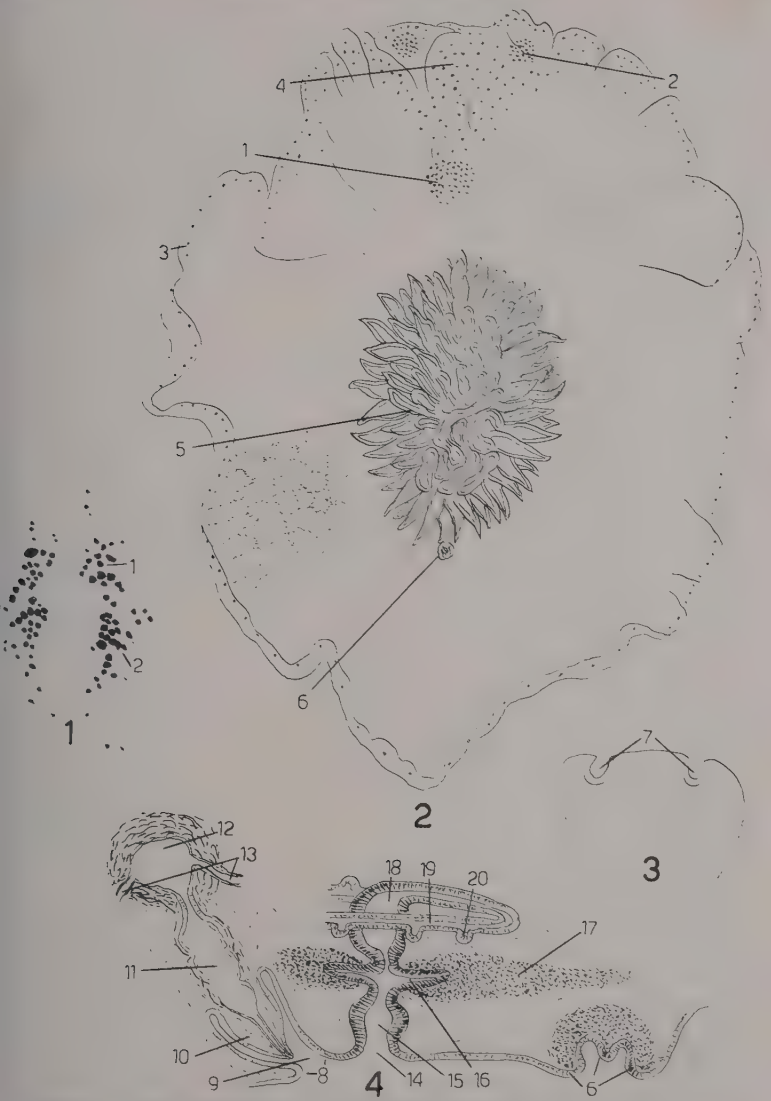


FIGURE 1. Eye arrangement of *Notoplana ferruginea*, Jamaica specimen.
FIGURE 2. *Pericelis orbicularis*, dorsal view from whole mount.
FIGURE 3. Same, tentacular folds in life; from a sketch provided by Dr. C. E. Dawson.
FIGURE 4. Same, sagittal view of the copulatory apparatuses.
1, cerebral eyes; 2, tentacular eyes; 3, marginal eyes; 4, cerebrofrontal eyes; 5, pharynx; 6, sucker; 7, tentacular folds; 8, male gonopore; 9, male antrum; 10, penis papilla; 11, prostatic vesicle; 12, seminal vesicle; 13, sperm ducts; 14, female gonopore; 15, female antrum; 16, cement pouch; 17, cement glands; 18, vagina; 19, uterus; 20, uterine vesicles; 21, main intestine; 22, mouth; 23, penis stylet.

Suborder *COTYLEA*
Family PERICELIDAE

Definition: Cotylea with eyes completely encircling the margin; with a pair of infolded marginal tentacles, each bearing a cluster of eyes; pharynx large, highly ruffled, central; copulatory apparatus and sucker in the posterior body third; uteri extending forward, bearing numerous uterine vesicles.

Genus *Pericelis* Laidlaw, 1902

Marcusia Hyman, 1953
Definition: With the characters of the family.

Pericelis orbicularis (Schmarda), 1859
Figures 2-4

Eurylepta orbicularis Schmarda, 1859
Pericelis orbicularis Stummer-Traunfels, 1933

Three specimens of this interesting species were sent by Dr. C. E. Dawson who had collected them under rocks in the intertidal zone at Cline's Point near the Institute of Marine Science, Port Aransas, Texas, in April and June, 1955. The species was hitherto known only from Jamaica, the type locality, but has not been found there since Schmarda's time.

The worm is of broadly oval form, reaching a length when alive, extended, of about 35 mm. According to Dr. Dawson's observations on the living animal the form is orbicular only in rest, being oval and with little ruffling of the margin when in motion. Along the margin, somewhat ruffled, in preserved specimens, runs a band of eyes that anteriorly includes a pair of clusters (Fig. 2). In life these clusters are borne on a pair of tentacular infoldings (Fig. 3) but these folds are not evident in preserved material. A group of eyes, scarcely paired, overlies the brain region and from these cerebral eyes cerebro-frontal eyes spread to the anterior margin in a fanlike manner (Fig. 2). The color pattern consists of a reddish brown network on a paler ground and is shown over a small area in the lower part of Figure 2. The voluminous pharynx with numerous pointed folds occupies the central part of the worm and is well seen in the cleared specimen. The sucker diagnostic of cotyleans occurs shortly behind the pharynx.

The copulatory apparatus is located at the posterior border of the pharynx, thus in the posterior third or fourth of the body, a very unusual position in cotyleans, and from the apparatus the uteri extend

forward, also something unusual in cotyleans. Stummer-Traunfels (1933) gave a good figure of a sagittal section of the copulatory apparatus of the original Schmarda specimen and I present a similar view in Figure 4.

Male and female copulatory apparatuses open close together into a depression that practically constitutes a common gonopore. From this the more anterior male apparatus ascends obliquely forward, presenting a conical or mammiform penis papilla succeeded proximally by an enlongated part with widened lumen and thin wall. This is considered a prostatic vesicle in the literature but I found no evidence of prostatic secretion. At the proximal end of this vesicle the male canal narrows and then opens into the seminal vesicle, a rounded body with large lumen and heavy muscular wall. This receives the two sperm ducts asymmetrically, one from behind, the other from below. Whereas the male apparatus is not all cotylean in structure, the female apparatus is typically cotylean. The female antrum with thick epithelial wall ascends and opens into the cement pouch, laterally expanded but dorsoventrally flattened, receiving the secretion of the large surrounding mass of cement glands. The vagina continues from the cement pouch, curving backwards and ending with the entrance of the two uteri that proceed anteriorly, receiving numerous small uterine vesicles. Shortly behind the female apparatus is found the sucker, here a large mass of infolded epithelium surrounded by a thick layer of eosinophilous glands.

There are known at present three species of *Pericelis* that complete the circuit of the tropics: *P. byerleyana* (Collingwood), 1876, widely spread in the Indo-Pacific from the eastern coast of Africa through the islands of Indonesia; *P. ernesti* (Hyman), 1953, from the Panamic region; and the present species from the West Indian region. All three have the same external appearance, the same eye arrangement, and the same reticulate color pattern. I have reexamined the type sections of *P. ernesti* which I mistook for an acotylean of the family Cryptocelidae and for which I created the genus *Marcusia*, here placed into synonymy with *Pericelis;* and I find that *P. ernesti* is definitely distinct from the other Pacific species, *P. byerleyana*. It has a well-developed sucker that I previously overlooked.

Family Pseudoceridae

Thysanozoon nigrum Girard, 1851

A specimen collected June 24, 1955, on a rock at South Jetty, Port Aransas, Texas, was sent by Dr. Dawson. This species was hither-

to known to Bermuda, the Bahamas, and both coasts of Florida (Hyman, 1952, 1955).

Pseudoceros texanus, new species
Figures 5, 6

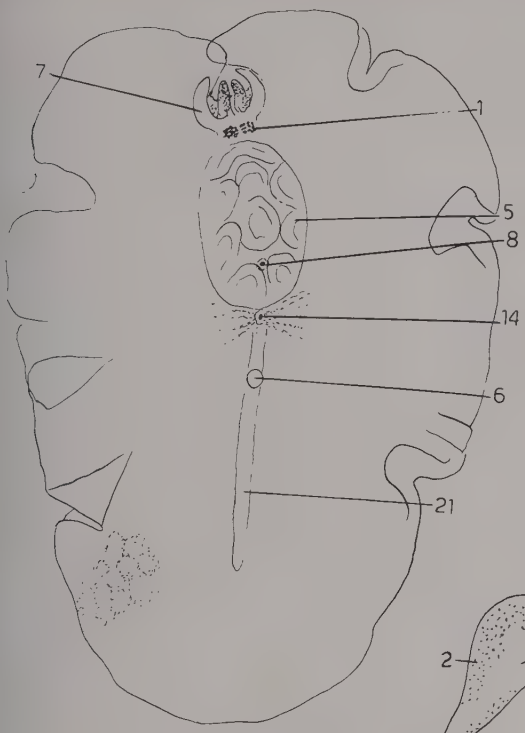
Four specimens were sent by Dr. Gordon Gunter of the Institute of Marine Science, Port Aransas, Texas, where they had been collected by W. C. Guest during July and August, 1954, on oyster shells suspended in wire baskets from the laboratory dock.

The worms are of oval form (Fig. 5), measuring when alive, extended, 20 to 30 mm in length by 10 to 15 mm in breadth. The tentacles, bearing many eyes, are of the usual *Pseudoceros* type but are strongly contracted in the specimens as a result of preservation. Shortly behind the tentacle bases is seen the pair of cerebral eye clusters, followed immediately by the ruffled pharynx occupying an oval area (Fig. 5). The female gonopore encircled by streamers of cement glands occurs directly behind the pharynx and the sucker is located slightly more than 1 mm behind the female gonopore. The color was stated as gray or purplish gray, arranged in a reticulate pattern, shown in a small area in Figure 5.

Sagittal sections of the copulatory apparatus (Fig. 6) reveal typical pseudocerid conditions except for the unusual location of the male apparatus beneath the pharynx with the penis papilla not far behind the mouth. The male gonopore, a little farther back, leads by a forwardly slanting passage to the antrum surrounding the penis papilla. The latter is provided with the usual stylet and embraced by the fold of the penis sheath as usual in the Pseudoceridae. An oval prostatic vesicle and long, muscular seminal vesicle join ducts in the penis papilla. The forward location of the male apparatus obtains in both of two specimens sectioned. It appears improbable that it could result from contraction on fixation.

The female apparatus offers nothing distinctive. A large antrum with folded walls leads into an oval cement pouch encircled by a great mass of cement glands. From the cement pouch the vagina arches posteriorly.

The possibility of the identity of these specimens with *Pseudoceros maculosus* Pearse, 1938, has been carefully considered and rejected. Pearse's species is described as having a maculate color pattern, a papillate dorsal surface, and two vesicles attached to the vagina whereas in the present species the color pattern is reticulate, the dorsal



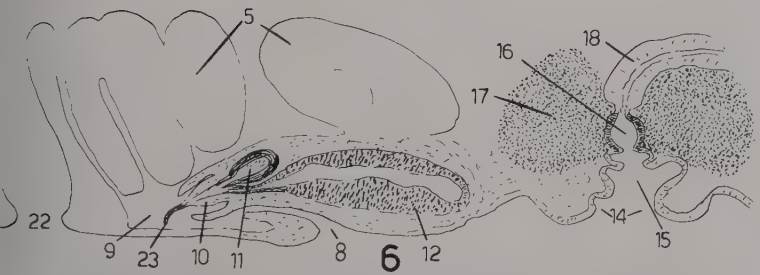


FIGURE 5. *Pseudoceros texanus,* dorsal view from whole mount.
FIGURE 6. Sagittal view of the copulatory apparatuses of *P. texanus.*
FIGURE 7. Tentacular folds and eyes of *Prostheceraeus zebra,* from whole mount.
1, cerebral eyes; 2, tentacular eyes; 3, marginal eyes; 4, cerebrofrontal eyes; 5, pharynx; 6, sucker; 7, tentacular folds; 8, male gonopore; 9, male antrum; 10, penis papilla; 11, prostatic vesicle; 12, seminal vesicle; 13, sperm ducts; 14, female gonopore; 15, female antrum; 16, cement pouch; 17, cement glands; 18, vagina; 19, uterus; 20, uterine vesicles; 21, main intestine; 22, mouth; 23, penis stylet.

surface smooth, and uterine vesicles were not found in two sets of serial sections. Furthermore in *P. maculosus* the male pore lies close in front of the female pore at the posterior edge of the pharynx and the sucker is much farther behind the female pore (3 mm) than in *P. texanus*. *P. texanus* is peculiar among the species of *Pseudoceros* in the far anterior location of the male apparatus. It belongs among the species with a single male apparatus. Marcus (1950) called attention to the existence of the genus *Acanthozoon* Collingwood (1876) for pseudocerids with short dorsal papillae or tubercles and suggested that *P. maculosus* be transferred to this genus.

The holotype as a whole mount is deposited in the American Museum of Natural History, accompanied by one set of serial sagittal sections to show the anterior position of the male apparatus.

Family Euryleptidae

Prostheceraeus zebra, new species

Figures 7, 8

This species was first seen when a living specimen was sent by Dr. Harold Humm. It had been taken June 23, 1953, on a leaf of green alga at three meters' depth in the Gulf of Mexico near St. Mark's Light off Wakulla County, Florida. Subsequently in February. 1955, two specimens were obtained from the first culvert on the Palisadoes Road, Jamaica, crawling on sea weeds, and later three more were secured at Ocho Rios, Jamaica. The species appears to be constantly associated with vegetation.

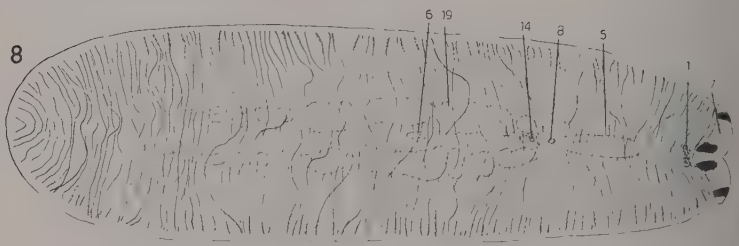


Figure 8. *Prostheceraeus zebra*, drawn from life, with details added from whole mount.

1, cerebral eyes; 2, tentacular eyes; 3, marginal eyes; 4, cerebrofrontal eyes; 5, pharynx; 6, sucker; 7, tentacular folds; 8, male gonopore; 9, male antrum; 10, penis papilla; 11, prostatic vesicle; 12, seminal vesicle; 13, sperm ducts; 14, female gonopore; 15, female antrum; 16, cement pouch; 17, cement glands; 18, vagina; 19, uterus; 20, uterine vesicles; 21, main intestine; 22, mouth; 23, penis stylet.

The appearance of the living animal when crawling, extended, is depicted in Figure 8. The elongated oval body reaches a length of 40-45 mm. At the anterior end are seen the thick tentacles, held erect in the moving animal, and shortly behind the tentacular bases occur the cerebral eyes in two clusters. The tentacular and cerebral eyes from a cleared preserved specimen are shown in Figure 7. Details added to Figure 8 from a cleared whole mount comprise the tubular pharynx, the male and female gonopores, the two uteri filled with eggs, and the sucker. The last is situated about 20 mm from the anterior end, hence slightly anterior to the middle.

The color pattern is distinctive and serves as sufficient recognition for the species. On a whitish or pale grayish brown ground occur numerous irregularly transverse black lines, that are slightly thickened at their ends. These lines end in a region tinted reddish or salmon, leaving a pale border free from markings. The tentacles as shown in Figure 8 have white tips and a white anterior border and are crossed by two black areas with an area between them of the same reddish or salmon hue as found near the border of the body.

Sagittal sections were made for the purpose of determining whether uterine vesicles are present. In the genus *Prostheceraeus* there is typically present a row of uterine vesicles on each side but none were found in the present species.

One whole mount has been deposited as holotype in the American Museum of Natural History.

Family Prosthiostomidae

Enchiridium periommatum Bock, 1913

Several specimens were taken in the culverts on the Palisadoes Road at Jamaica and in fact the species appears to be one of the more common Jamaican polyclads. The species reaches a length of 45 mm in life when crawling extended and has an elongated obovate shape. To the naked eye it appears dotted with brown on a white ground. Under magnification it is seen that the brown dots are intermingled with orange-buff ones and that the dots are more concentrated in the middorsal area, giving there somewhat the appearance of a stripe. I recently (Hyman, 1955) gave a figure of this polyclad and although the figure was made from a preserved specimen, it represents quite well the shape and coloration in life. Other details about this species appear in the article cited.

Enchiridium periommatum is probably spread throughout the

West Indian region, although so far taken only at Jamaica, the Danish West Indies, and the Gulf of Mexico off Florida.

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ECOLOGICAL OBSERVATIONS ON A LOCALLY LIMITED RED TIDE BLOOM[1]

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Abstract

In order to study the assumed importance of the passes in generating Red Tide outbreaks, the hydrographical tidal conditions were studied in the Boca Grande Pass. The results confirmed previous ones and indicated the two-layer character of this estuary. In the deeper water no *Gymnodinium brevis* was found. The heavier concentration was observed during all tidal phases on the side of Gasparilla Island, suggesting that they must have originated somewhere "behind Gasparilla Island" and not in the area of the highest total phosphorus. As a second, simultaneous part of the study, an effort was made to find the areas from which the *G. brevis* in this case originated. In two separate spots (Stations 12 and 20) actual, locally limited Red Tide kills were observed. An optimum salinity for the *G. brevis* appeared to exist between 32 and 33 parts per thousand. A diurnal vertical migration of *G. brevis* was observed.

Introduction

The research vessel, M/V PHYSALIA, carried out hydrographic and other Red Tide investigations off the west coast of Florida in November and December 1954. From these studies several independent results have come out. This report is a preliminary one on a special study made during the above period.

In the Preliminary Report (54-19) on the Red Tide studies from January to June 1954, submitted by the Marine Laboratory to the Florida State Board of Conservation, it was stated on the basis of previous observations that, (page 14) "the initial outbreak is usually observed as dying fish in the passes. Since the net flow in the passes is outwards, it is most probable that the origin of Red Tide must be inside the barrier islands . . . The most important passes, as to the first observation of Red Tide, seem to be Boca Grande Pass, Captiva Pass, and Gasparilla Pass."

In order to study the presumed importance of the passes in the origin of the Red Tide, an importance doubted by some Red Tide workers, attention was first given to hydrographic tidal conditions in the Boca Grande Pass itself. The main goal of this part of the study was to find out in which type of water the heaviest concentration of

[1]Contribution No. 152 from the Marine Laboratory, University of Miami.

Gymnodinium brevis was to be found. A second simultaneous study was made to find the areas from which *G. brevis* immediately originated.

This study was made possible by the fortunate occurrence of a locally limited Red Tide bloom in the area concerned. Thus it was possible to perform observations under the actual conditions of an initial Red Tide outbreak.

I. Hydrographic Conditions in the Boca Grande Pass in Relation to *Gymnodinium brevis*

Observations. The stations A-G (Figure 1) were occupied three times on December 1, 1954, once during the maximum ebb, once during the slack after ebb, and once during maximum flood. The location of the stations was the following:

A: 26° 42′ 32″ N., 82° 15′ 27″ W.
B: 26° 42′ 38″ N., 82° 15′ 33″ W.
C: 26° 42′ 54″ N., 82° 15′ 39″ W.
D: 26° 42′ 38″ N., 82° 14′ 50″ W.
E: 26° 42′ 58″ N., 82° 15′ 03″ W.
F: 26° 43′ 19″ N., 82° 15′ 15″ W.
G: 26° 43′ 39″ N., 82° 15′ 27″ W.

Observations, during the maximum ebb, were performed between 0730 and 0940, during the slack after ebb between 1215 and 1317, and during maximum flood between 1700 and 1812. The darkness and the shallow water made it impossible to occupy station G for a third time.

The day of observation was almost cloudless with less than 1/10 of the sky, above the land, covered with cumulus clouds during the noon hours, which later flattened into altocumulus and finally disappeared after sunset. When the observations were started at 0730, the air (65.0° F) was 3.6° F cooler than the sea surface (68.6° F). At 0945 both showed the same temperature, 68.3° F. At 1317 it was observed that the air (73.6° F) was 3.8° F warmer than the sea surface (69.8° F), while around the time of sunset, about 1800, both showed the same temperature, 69.5° F. During the morning hours the winds were from 30° to 60°, 8-10 knots, during the noon hours they were from 30° to 35°, 3-4 knots and during the later afternoon hours from 300° to 310°, increasing from 9 to 13 knots. Thus the wind observations mainly indicated the effect of land and sea breeze. The sea was, during the morning and noon hours, practic-

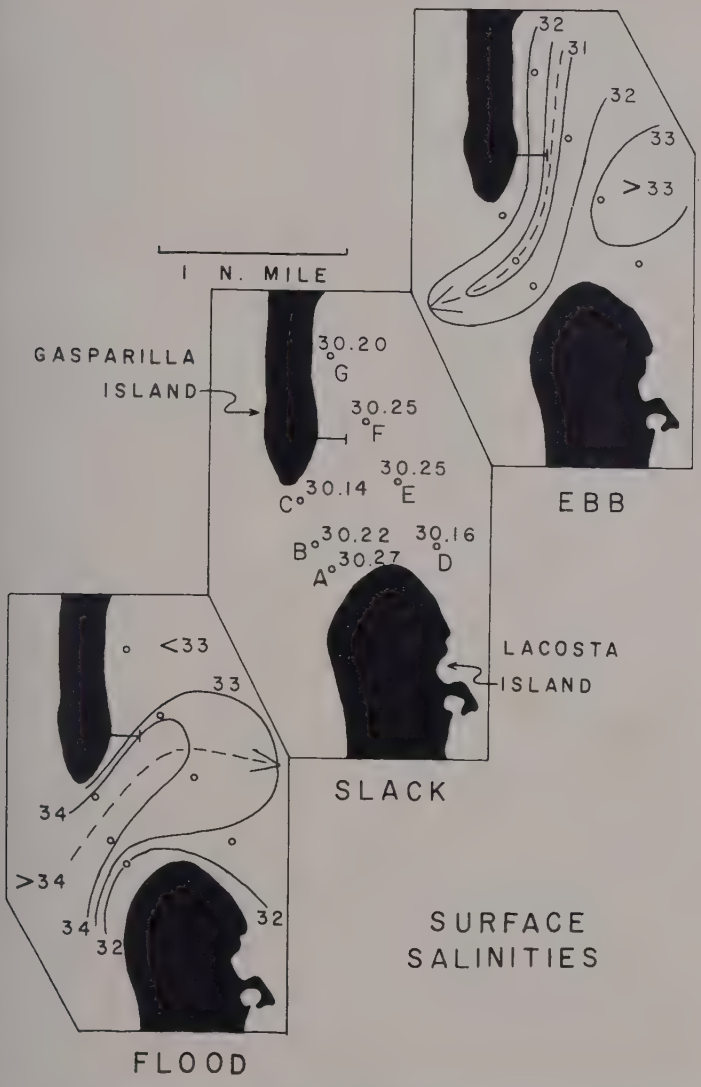


FIGURE 1. Surface salinities around Boca Grande Pass during maximum ebb, during slack after ebb, and during maximum flood.

ally smooth (0-1) but during the later afternoon hours slight wave action (1) was observed. Hence conditions were ideal for the study.

The main sections between stations A and C consisted of the following observations:

Gymnodinium brevis count; surface and bottom (Figure 11).
Salinities, surface and bottom, also mid-depth at Station C (Figure 2).
Surface temperatures (Figure 3).
Vertical distribution of temperature, by bathythermograph (Figure 3).
Densities, computed from the salinities and temperatures for the depths with salinity observations (Figure 4).
Vertical distribution of current speeds, measured by means of the Von Arx current meter, for several depths (Figure 8).
Total phosphorus, surface and bottom (Figure 9).
NO_3-N, surface only (Figure 10).
NO_2-N, surface only.
p_H, surface only.
Wind, direction and speed.
Air temperature.
Wet bulb temperature.
Cloudiness, type and cover.
Visibility.
Sea.

The auxiliary sections, between stations D and G, consisted of the following observations:

Salinities, surface and bottom (Figure 5).
Surface temperatures (Figure 6).
Vertical distribution of temperature, by bathythermograph (Figure 6).
Densities, computed from the salinities and temperatures for the depths with salinity observations (Figure 7).
Wind, direction and speed.
Air temperature.
Wet bulb temperature.
Cloudiness, type and cover.
Visibility.
Sea.

The limited time available for observations made additional observations impossible. For the same reason it was necessary to limit

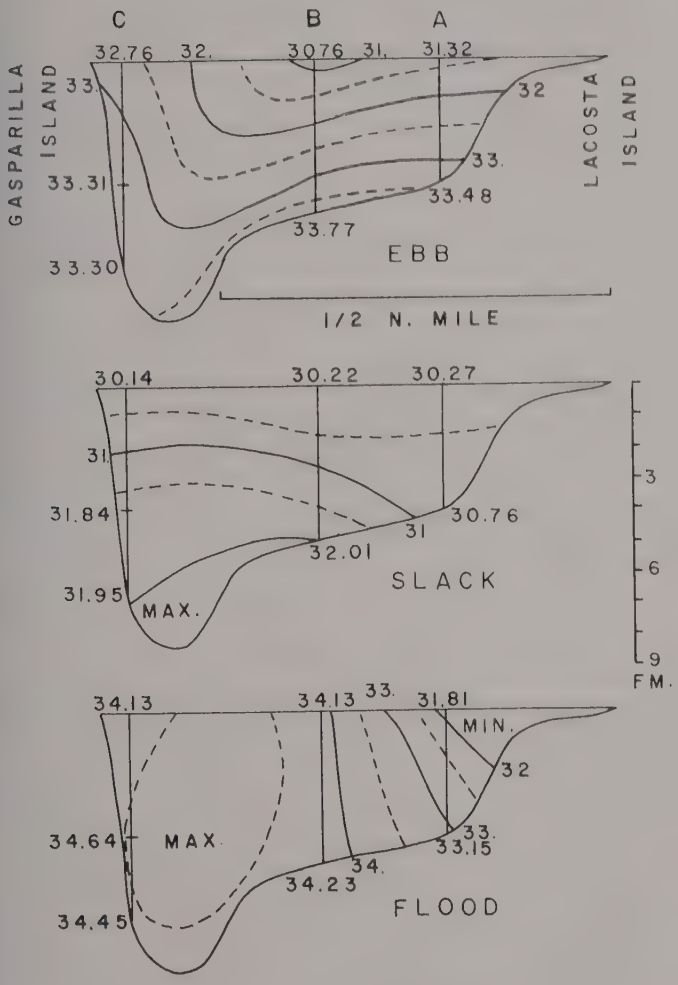


FIGURE 2. Transverse salinity sections across Boca Grande Pass.

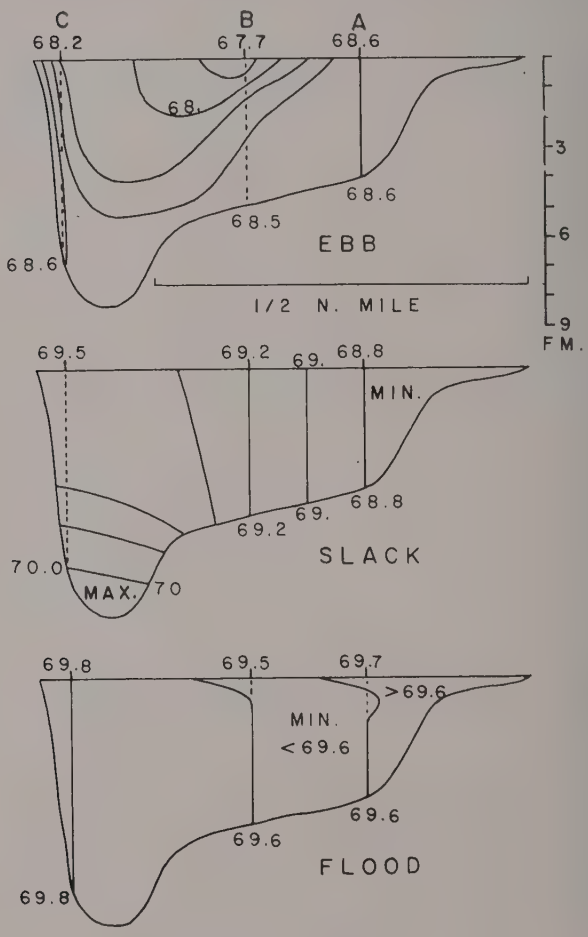


FIGURE 3. Transverse temperature sections across Boca Grande Pass.

the number of stations of the main section, A-C, to three. Later when plotting the different sections, it became evident that four stations with more depths would have covered the situation better than three, although it is believed that the short mean distance between stations A, B, and C, being only slightly above 300 yards, is rather unique in marine studies. Due to the limited number of stations, in some cases apparent minor inconsistencies can be observed in the patterns of representations of single elements, since sections were drawn independently and strictly following the method of interpolation. No attempt was made to adjust the different sections to each other which would easily have eliminated the apparent inconsistencies.

Hydrographic (Tidal) Conditions. In connection with another study of this author (The Marine Laboratory, 1954) performed on the tidal influences on the hydrography of the Boca Grande Channel, it was shown that in the whole Channel the salinities are practically always lower at the surface than at the bottom, which indicates that a strong hydrographic influence of the two-layer estuary must have extended at least some four miles off the Pass. The salinity sections between the Gasparilla and Lacosta Islands (Figure 2) show the same quite clearly for the ebb tide. However, at the maximum flood, the two-layer character of the Pass is almost destroyed by the flood waters which fill a good portion of the Pass. The same is roughly seen also from the temperature sections (Figure 3) which are, however, partly masked by the diurnal heating and cooling effects. Finally, the density sections (Figure 4) mainly verify the greater significance of salinity compared to temperature. In particular, it is seen clearly that the ebbing, less dense water is imbedded between more saline waters along the shorelines.

The auxiliary sections D-G, inside the Boca Grande Pass (Figures 5, 6, and 7), show corresponding conditions. The surface salinities are shown also as Figure 1, which clearly shows how the ebbing waters are in this case originated east of the Gasparilla Island and not directly east of the Pass. After having left the Pass, the ebbing waters take a westerly direction following the course of the Boca Grande Channel, but the flooding waters probably come from the region south of the Pass. These waters after having penetrated the Pass, follow an easterly or, possibly, an eastsoutheasterly course. Thus this mechanism indicates how the coastal water patches may be formed in the narrow pass by the flood current completely cutting off each ebbing water movement.

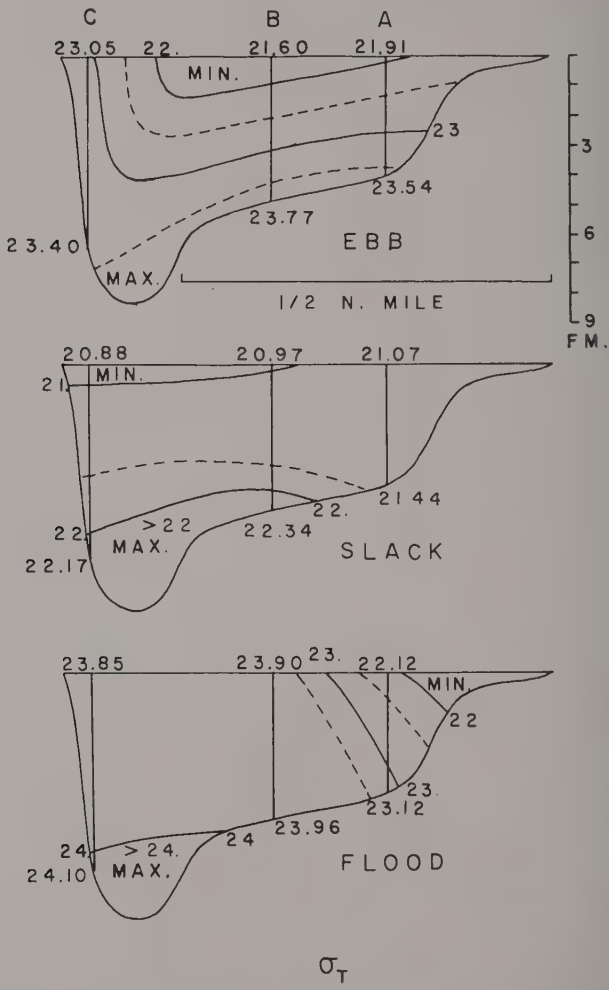


FIGURE 4. Transverse density (σt) sections across Boca Grande Pass.

The current observations (Figure 8) show that the ebb current actually takes a path rather close to the northern edge of the Boca

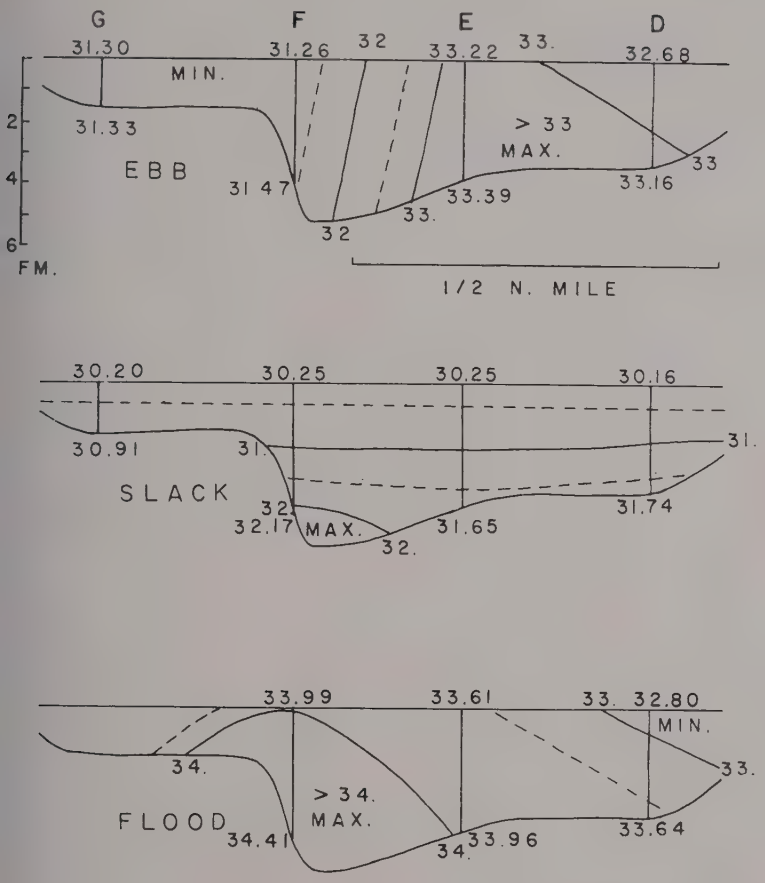
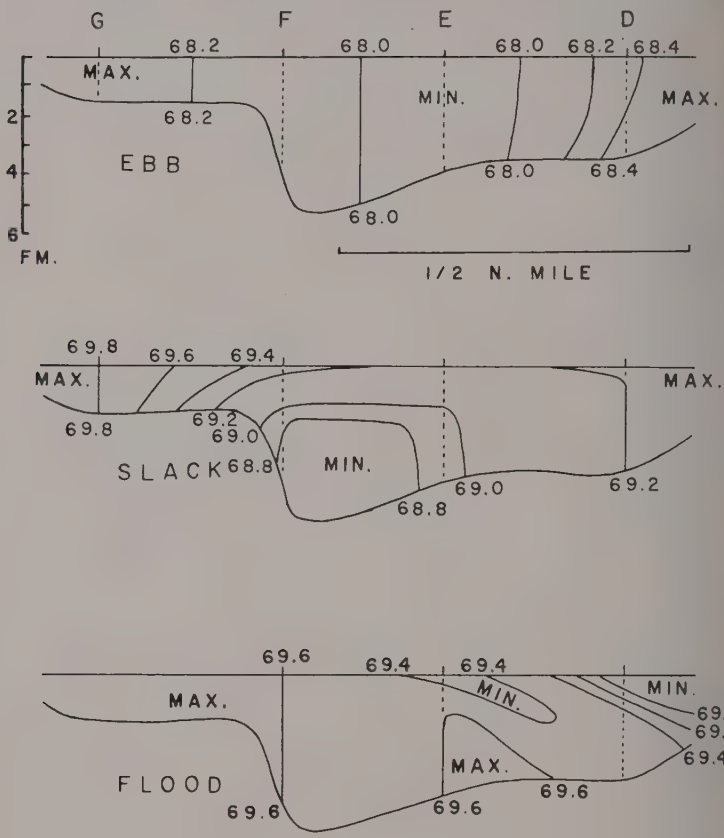


FIGURE 5. Transverse salinity sections inside Boca Grande Pass.

Grande Pass, while the flood current stays in the middle portion of the Pass. The current measurements were made by means of a Von Arx current meter which gives only the speeds (in knots) but not direction. In the rather shallow Boca Grande Pass the direction



TEMPERATURES

FIGURE 6. Transverse temperature sections inside Boca Grande Pass.

of current is apparently always determined mainly by the topography of the Pass, and could always be estimated from the direction of the fin. In this connection, it is necessary to observe that an additional station between B and C would have been very useful for the deter-

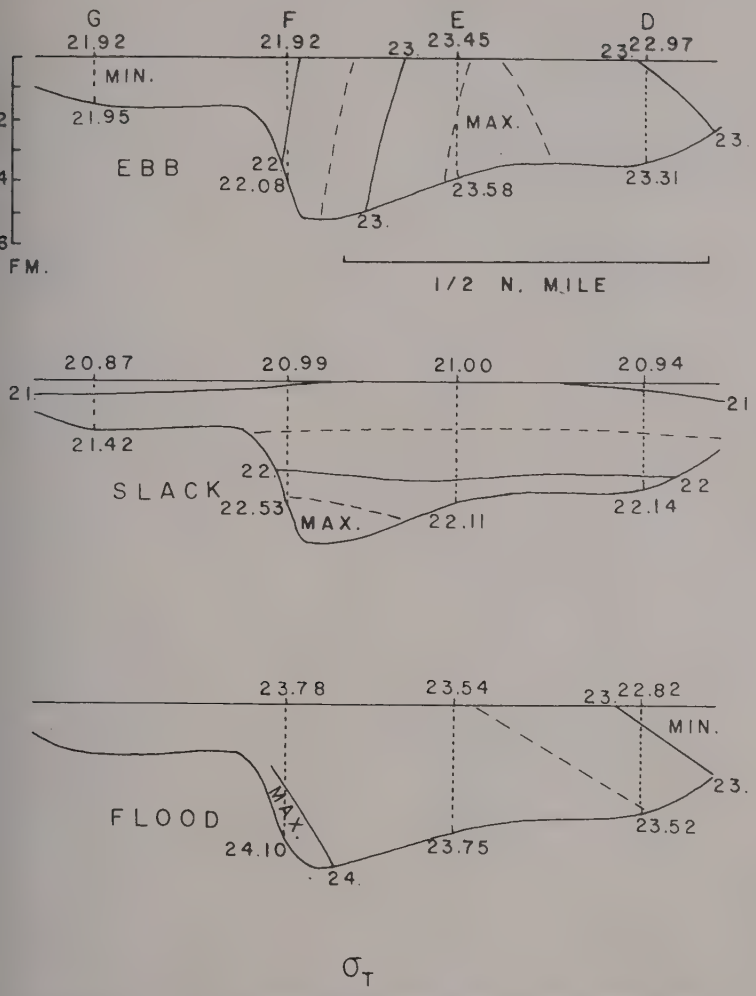


FIGURE 7. Transverse density (σt) sections inside Boca Grande Pass.

mination of the northern limit of the strong flood current (Figure 8) and, similarly, of the exact location of the salinity borders of the ebb and flood currents (Figures 1 and 2). Due to this lack of the additional station, some inconsistency may be seen between the Figures

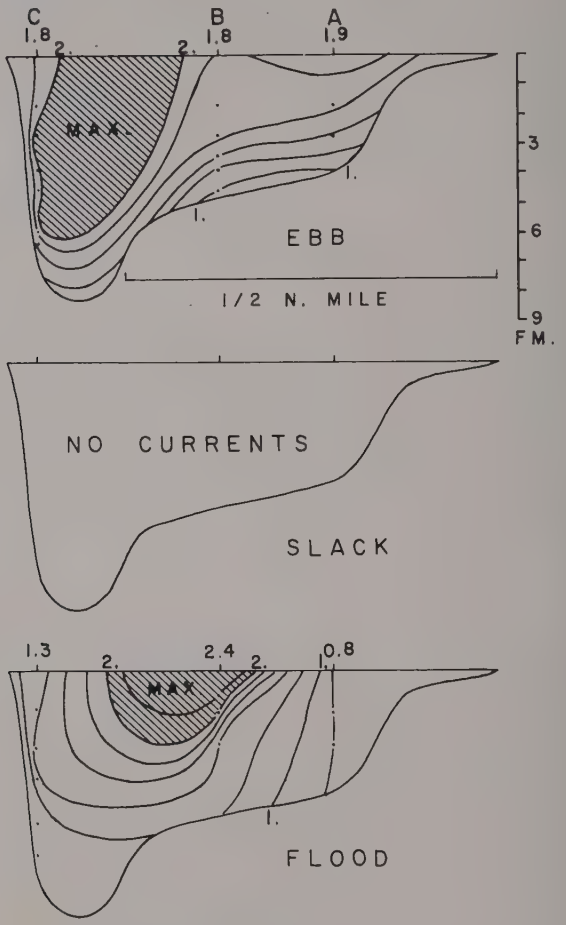


FIGURE 8. Transverse sections of current speed across Boca Grande Pass. The speeds are given in knots.

2 and 8. These apparent inconsistencies are brought about by interpolation and are most probably not real.

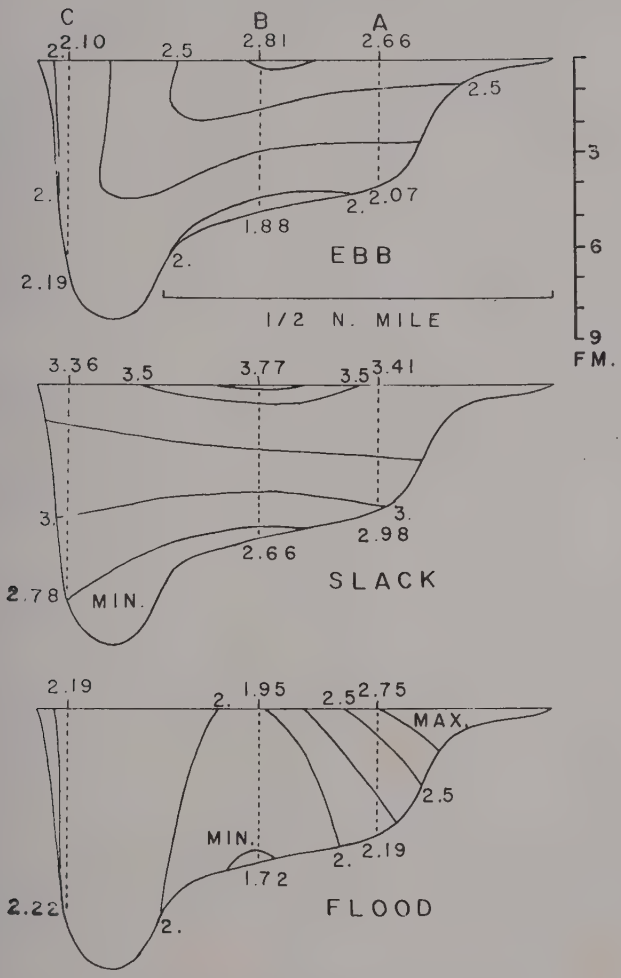


FIGURE 9. Transverse sections of total phosphorus across Boca Grande Pass. The concentrations are given in μga/L.

The distribution of total phosphorus concentration is shown as Figure 9 in μga/L. Generally it has been assumed that the total

phosphorus in this area indicates the existing, or the hypothetically possible highest, concentration of *Gymnodinium brevis*. It is seen again here that the higher total phosphorus is found in the ebbing water while the lower concentrations are encountered in the flood current. However, when these distributions are compared with Figure 11, which shows the *G. brevis* concentrations (in a logarithmic scale) it becomes evident that the origin of the latter must have been somewhere "behind the Gasparilla Island" and not simply in the area of the highest total phosphorus.

Probable distributions of the NO_3-N are shown in Figure 10, which is based upon surface observations only and which seems to indicate the existence of littoral effects. The NO_2-N distribution was the following at the surface:

	A	B	C
Maximum ebb	.19	.20	.17
Slack after ebb	.18	.15	.20
Maximum flood	.18	.16	.17

And finally the p_H varied in the following way at the surface

	A	B	C
Maximum ebb	8.4	8.4	8.4
Slack after ebb	8.3	8.3	8.3
Maximum flood	8.5	8.5	8.6

GYMNODINIUM BREVIS. The *Gymnodinium brevis* concentrations (Figure 11) are given in a logarithmic scale showing the number of individuals per liter. From the schematic drawings it can be seen (i) that in the deeper water no *G. brevis* were found during the period of observation covering one daylight day; (ii) that during all tidal phases the heavier concentration was observed adjacent to Gasparilla Island; and (iii) that at the maximum ebb current a heavy concentration was seen only at station C, but later at the slack after ebb, it also appeared at station B. The flood current again pushed the heavy concentration more or less against the southern shoreline of Gasparilla Island, station C.

II. THE ORIGIN SPOTS OF *Gymnodinium brevis* FOUND IN THE BOCA GRANDE PASS

Sampling for GYMNODINIUM BREVIS *around Gasparilla Island.* In addition to the surface and bottom water samples for *Gymnodinium brevis* counts, referred to above, samples were taken in a longitudinal

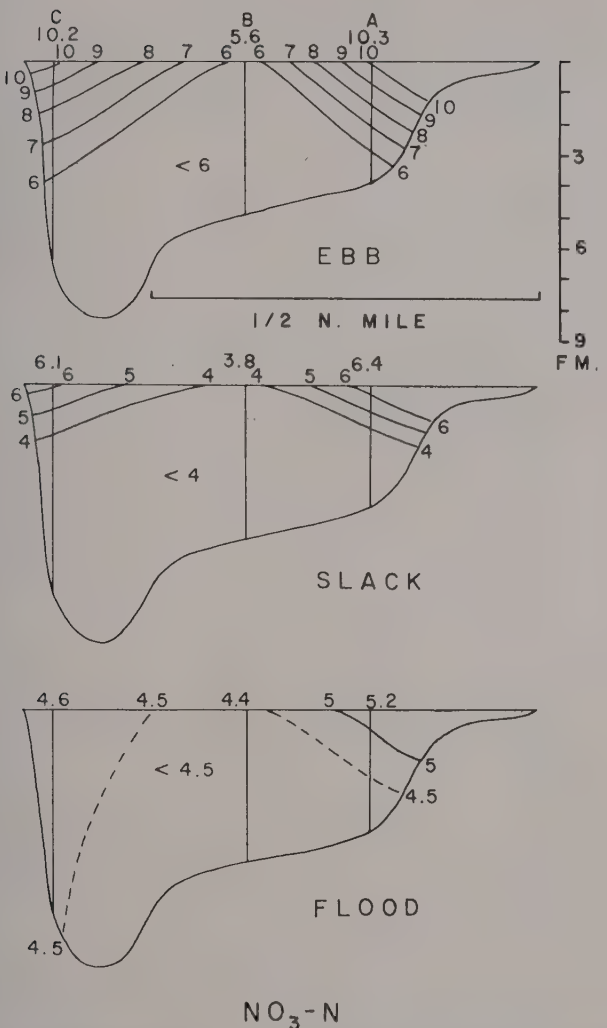


FIGURE 10. Transverse sections of NO_3-N across Boca Grande Pass. The concentrations are given in μga/L.

section west-southwest of Boca Grande Pass (Figure 12) and in shallow areas around Gasparilla Island (Figures 13 and 14). The

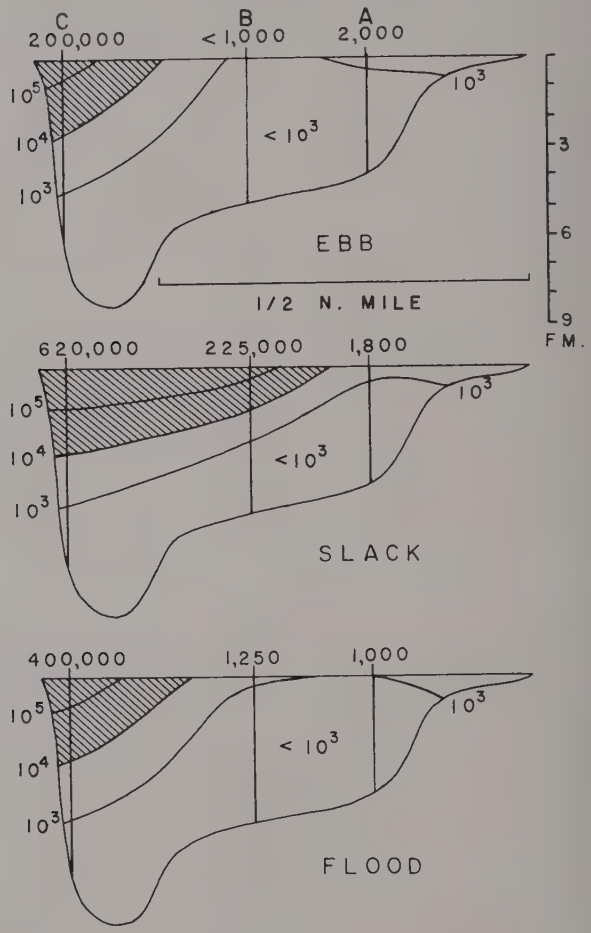


FIGURE 11. Transverse sections of *Gymnodinium brevis* concentration in Boca Grande Pass. The concentrations, in a logarithmic scale, are given as the number of cells per liter.

G. brevis counts were performed immediately after the sampling. At stations 12 and 20 actual fish kills were observed with *G. brevis*

concentration of over 10 million per liter, rather syrupy water, and with dying or dead fish. It is worthwhile mentioning that these observations, together with other facts previously reported here led to the establishment of a field laboratory on Gasparilla Island by The Marine Laboratory.

The Patchy Character of Offshore Concentration of GYMNODINIUM BREVIS. Red Tide biologists are aware of the fact that *Gymnodinium brevis* shows a patchy character in its concentration offshore. This fact was referred to in a previous report (Hela, 1955). The author also observed, in November 1954, a *G. brevis* concentration of 500,000 individuals per liter some 35 nautical miles west-southwest off Tampa Bay without any noticeable concentrations in adjacent

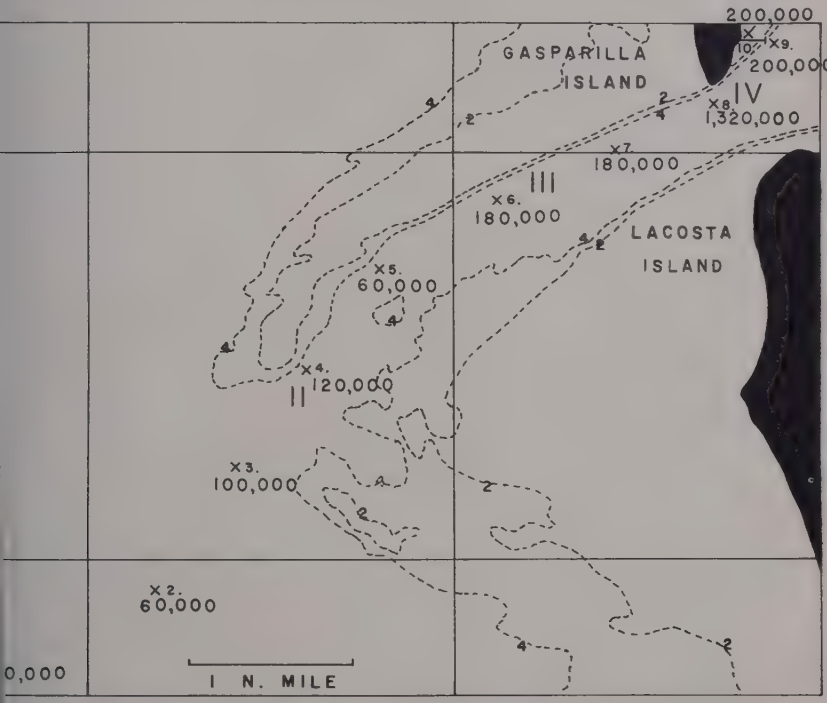


FIGURE 12. Longitudinal *Gymnodinium brevis* stations in Boca Grande Channel. The concentrations are given as the number of cells per liter.

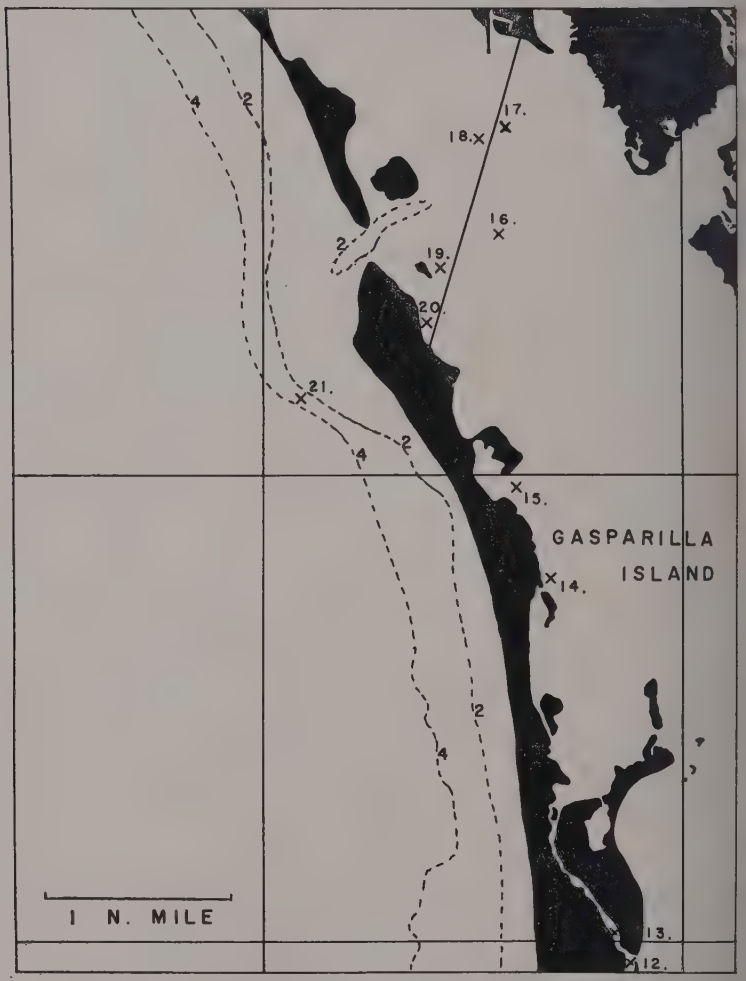


FIGURE 13. *Gymnodinium brevis* stations around Gasparilla Island.

waters. A later effort to find this high concentration, for purpose of another sampling, was not successful.

The patchy character of the offshore concentration of *G. brevis* can be understood, at least partly, when it is remembered that every ebb current takes a new patch of coastal water to the open Gulf. Also off Boca Grande Pass, as shown in Figure 12, the *G. brevis* concentration varied rather rapidly from station to station during a period of sampling of about 40 minutes. In this section, successive patches of coastal water may perhaps be indicated by *G. brevis* concentrations. They are shown in the Figure by the Roman letters, I-IV.

The Optimum Salinity for GYMNODINIUM BREVIS. The *Gymnodinium brevis* samples taken around the Gasparilla Island with salinity determinations make it once more possible to plot the *G. brevis* counts against the salinity (Figure 15) in an attempt to find optimum salinity for *G. brevis* in natural waters. It is seen rather clearly from this logarithmic representation that maximum concentrations appear around 32 to 33 parts per thousand. This is not necessarily an optimum condition. It is at least possible, however, that the data show that a local Red Tide bloom occurs only where all the other factors, such as radiation, shallowness, exposure, etc., are or have been favorable for the bloom and where the salinity is about, say, 31 to 34 parts per thousand.

Vertical Migration of GYMNODINIUM BREVIS. In Figure 16 all the counts on *Gymnodinium brevis* samples, taken at surface during the period of study around the Gasparilla Island, are plotted against the time. The location of the sampling stations can be seen from Figures 13 and 14. The schematic curve through the dots is drawn to emphasize the possible diurnal character in the surface concentration of *G. brevis*. It is evident that the *G. brevis* seems to leave the surface during the night and rise during the day. It is emphasized that even the syrupy character of the surface water at the very shallow stations 12 and 20, at which the highest *G. brevis* concentrations were found, simply disappeared rapidly around sunset without any observable external cause, such as an advective water movement, other than the disappearing daylight. Efforts have been made to connect the above changes in the concentration also with tidal or other advective causes, but the above changes seem to be main'y phototactic. Therefore, another study is planned to observe in a suitable spot the actual vertical migration of *G. brevis*.

That vertical migration in marine Dinoflagellates in the above

FIGURE 14. *Gymnodinium brevis* stations around Gasparilla Island.

sense is possible as shown by Hasle (1950) who studied the problem in the inner and relatively shallow Oslo fjord. "The following dino-

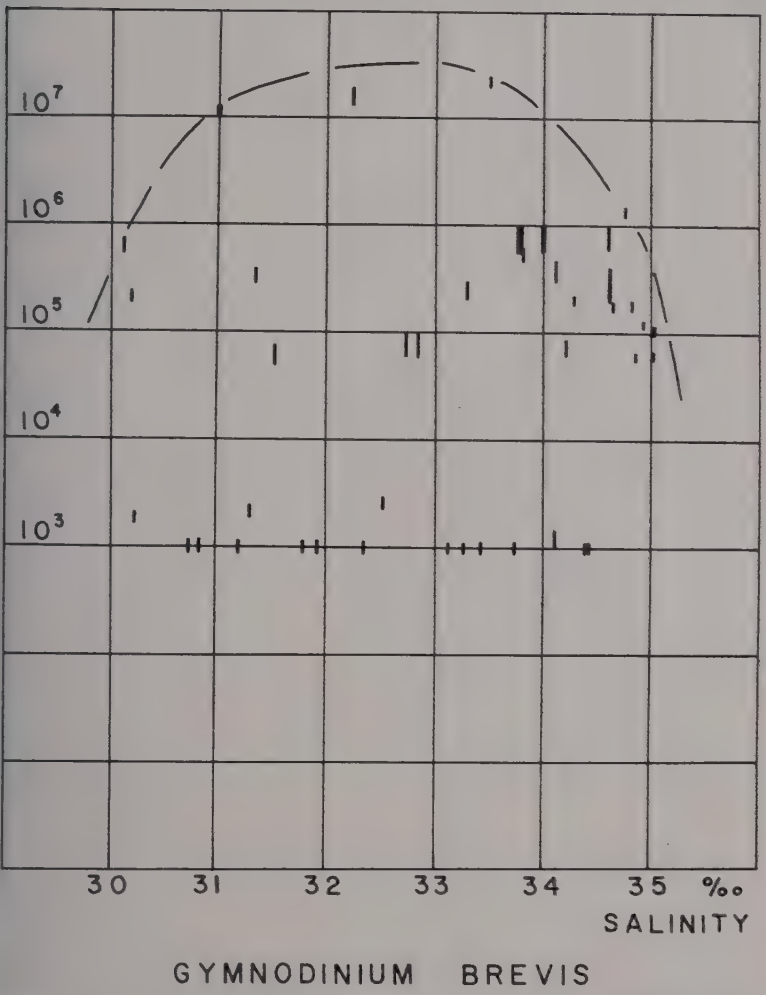


FIGURE 15. Concentrations of *Gymnodinium brevis* around Gasparilla Island plotted against salinity.

flagellates were studied: *Ceratium fusus* and *C. tripos, Gonyaulax polyedra* and *Prorocentrum micans* . . . Two distinct types are found. The two *Ceratium* species belong to one type: The population at the

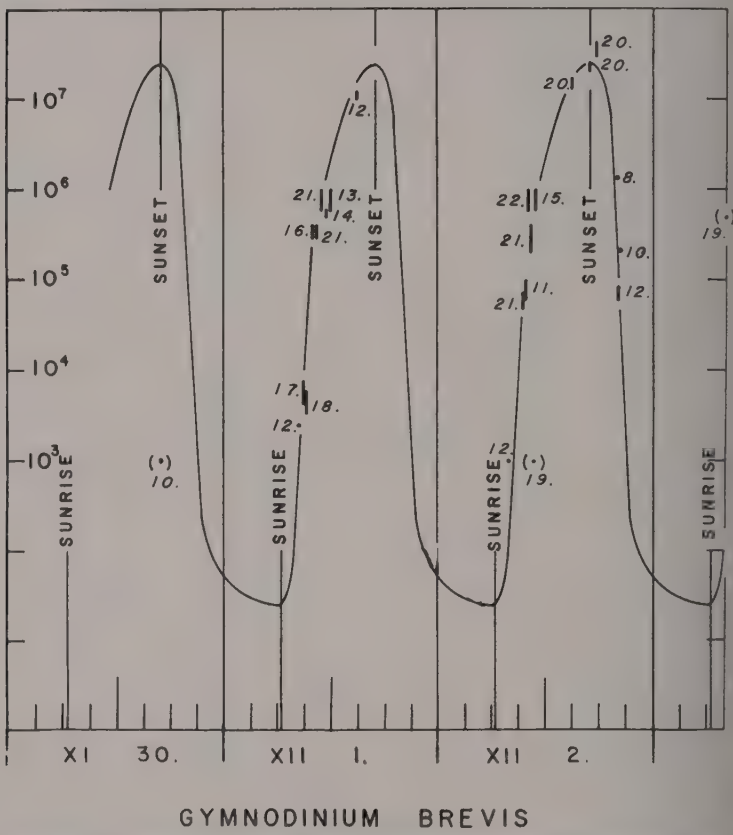


FIGURE 16. Concentrations of *Gymnodinium brevis* around Gasparilla Island plotted against time.

surface . . . seem to decrease as the light intensity increases, which means that the ceratia leave the surface during the day and rise at night. . . . *Gonyaulax polyedra* and *Prorocentrum micans* represent the second type. The curves for the population at the surface . . . and for the intensity of daylight follow much the same trend. These species leave the surface during the night and rise during the day. In *Prorocentrum micans* the maximum number at the surface was, however,

recorded from about 12.00 hr., while in *Gonyaulax polyedra* it occurred considerably later, between 16.00 and 18.00 hr., when maximum of daylight intensity had passed some time before."

When further studies have definitely verified the character of the vertical migration of *G. brevis,* as suggested above, the effects of radiation and of the shallowness of the sea area may be taken into consideration anew as vital ecological factors for the development of local Red Tide blooms.

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A REDESCRIPTION OF THE MARINE ISOPOD CRUSTACEAN *"EXOSPHAEROMA" FAXONI* RICHARDSON FROM TEXAS[1]

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ABSTRACT

Exosphaeroma faxoni Richardson is placed in the genus *Cymodoce* and redescribed on the basis of specimens collected at Port Isabel, Texas and the type specimen from Florida. This is the first indigenous species of *Cymodoce* reported from North America.

The species *Exosphaeroma faxoni* Richardson was described in 1905 from one male specimen taken in Florida by Professor A. S. Packard. The type is located in the Museum of Comparative Zoology at Harvard College, Cambridge, Massachusetts, Cat. No. 6732, M. C. Z.

Several specimens from Port Isabel, Texas, which suspiciously looked like the drawings of this species (Richardson, 1905, fig. 307) were sent to us for determination by their collector, Dr. Joel Hedgpeth, then with the Institute of Marine Sciences, University of Texas. Port Aransas, Texas. Several discrepancies were noted. First, the specimens from Port Isabel belonged to the genus *Cymodoce* and not to *Exosphaeroma*. This is a matter of considerable importance for its own sake since only one other species of the genus *Cymodoce* had been previously reported from North America and this species, *C. japonica* Richardson (Hatch, 1947, p. 215), is believed to have been introduced into America from Japan along with the Japanese oyster. This then constitutes the first record of an indigenous species of *Cymodoce* from North America. The second item of concern was the fact that the pleon of *E. faxoni* is figured as having four complete segments plus the lateral incisions of a partly coalesced fifth. This would be an unusual state of affairs for most sphaeromid genera and would not allow the placement of *E. faxoni* in either *Exosphaeroma* or *Cymodoce*. Richardson (op. cit., p. 292) remarked, however,

[1]Contribution from the Department of Zoology, University of California, Davis, California and the Scripps Institution of Oceanography, new series, 000.

"The abdomen is composed of two segments." Our specimens had a pleon (abdomen, Fig. 1E) composed of *three* segments as is usual for many sphaeromids. The first is small and concealed by the last peraeonal somites except for parts of its lateral margin. The second and third are about as Richardson describes.

Dr. Elisabeth Deichmann, Curator of Invertebrates at the Museum of Comparative Zoology at Harvard College, generously aided us in our problem by providing us with sketches of the type and by comparing the figures given here with the type. She found the type specimen to agree favorably with our figures and accordingly, we have arrived at the conclusion that Hedgpeth's Texan specimens of *Cymodoce* and Richardson's *Exosphaeroma faxoni* are probably one and the same species.

Richardson did not describe several anatomical features which are important today in isopod taxonomy and these we give in the following description.

Cymodoce faxoni (Richardson) comb. nov.
Figures 1A-J, 2A-K

Synonyms. Exosphaeroma faxoni Richardson, 1905, pp. 292-293, figs. 307-308.

Diagnosis. Pleon composed of a narrow first somite which is concealed from dorsal view except near the lateral margins by the seventh peraeonal somite, a longer second somite which is formed by the fusion at the mid-line of three pleonal somites (pleonites), and a pleotelson which is twice as long as the rest of the pleon. Last pleonite with a pair of medially located swellings at posterior margin. Pleotelson with a similar but more obvious elongated pair of swellings at central area. Posterior apical margin of pleotelson trifid. Uropodal exopod styliform, as long as endopod in female and one-third to one-half longer than endopod in male with the large males having the longest and most styliform exopods; endopod apically truncated, outer angle pointed. First antenna with first peduncular article elongate and swollen, second article as wide as long being one-third narrower and one-half as long as first; third article one-half narrower than second and four times as long as wide; fourth article small, partly concealed between third peduncular and first flagellar article; flagellum with about 10 articles. No antennular scale was found but three setae projecting between the third and fourth peduncular articles indicate where its vestige might be located. Peduncle

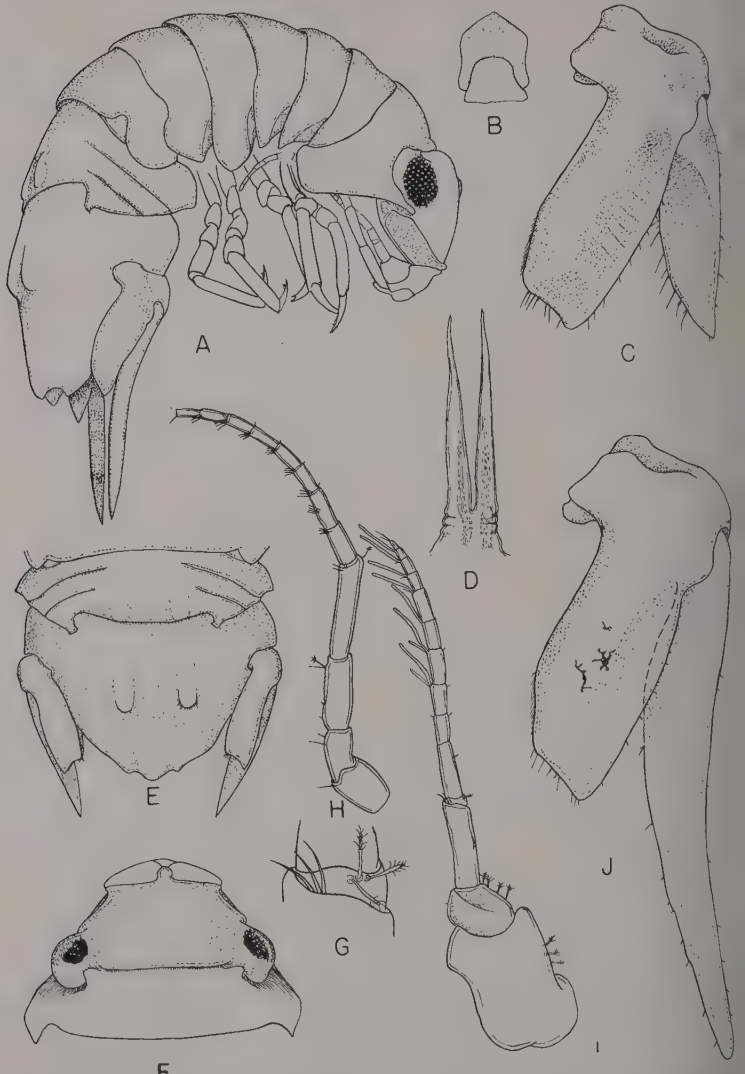

FIGURE 1. *Cymodoce faxoni* (Richardson). A. Male, lateral view, B. Clypeus and labium, C. Uropod, female, D. Genital apophyses, male, E. Pleon of young male, F. Cephalon and first peraeonal somite of female, G. Terminal peduncular article of first antenna, H. Second antenna, I. First antenna, J. Uropod of mature male.

FIGURE 2. *Cymodoce faxoni* (Richardson). A. Left mandible, male, B. Second maxilla, female, C. Apex of stylus of male second pleopod, D. Seventh peraeopod, male, E. Apex of endopod of male fifth pleopod, F. Second peraeopod, male, G. First maxilla, female, H. Maxilliped of female, I. Fourth male pleopod, J. Apex of endopod of fourth male pleopod, K. right mandible of female.

of second antenna with four articles of similar width, first and second subequal in length, third one-third longer than second, fourth one-third longer than third, flagellum with 14-15 articles. In dorsal view the frontal process of the cephalon is produced and apically pointed. It projects downward medially where it meets the frontal lamina (clypeus) thus separating the first peduncular articles of the first antenna medially. Genital apophyses (penes) elongate and styliform. Appendix masculinum of second male pleopod laterally recurved at apex.

Mouth parts of female metamorphosed, showing particularly a loss of setae. Mandible of female shows a diminution of the incisive process, a loss of the lacinia mobilis and of the setae of the setal row. Male maxilliped each with one coupling hook. Endopods of fourth and fifth male pleopods fleshy, each with eleven respiratory folds, apex of fourth with a distinctive emargination medially, that of fifth with two spinulate lobes.

Measurements. Male (figured), 5.4 mm long, 2.3 mm wide at first peraeonal somite. Female (not ovigerous), 4.8 mm long, 2.0 mm wide at first peraeonal somite.

Material examined. Two males, five females, collected 11-12-47 at South Bay, Port Isabel, Texas. The specimens have been donated to the Museum of Comparative Zoology, Harvard College, Cambridge, Massachusetts.

Remarks. This species appears to be closely related to *Cymodoce acuta* Richardson (1904, pp. 38-39, figs. 8-10). It differs from it in having a less pointed pleotelson and further in having the suture of the first pleonite (the first fused somite in the coalesced "second" pleonal somite) extending farther medially than that of the second. The reverse of this is shown in Richardson's figure (op. cit.). The species also resembles *C. japonica* Richardson but it differs from that species in having one pair of elevations medially on the pleon instead of two pair.

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HYDROGRAPHY OF THE DUPLIN RIVER, SAPELO ISLAND, GEORGIA[1]

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ABSTRACT

The circulation pattern of a tidal river which drains an extensive salt marsh area and which receives practically no fresh water is described in detail. This circulation is primarily tide-driven. Synoptic current velocity profiles and volume transport values are presented for various stages of the tide and for both neap and spring tides. It is shown that the flooding of the salt marsh may increase the volume of water involved in the tidal circulation of the river by fourfold with a corresponding increase in tide level of 50 percent. A method for determining the tidal excursion in a river of this type is developed and applied to the observed transport data. Biological implications of the observed circulation are discussed.

INTRODUCTION

Circulation patterns of estuaries have received considerable attention from hydrographers in recent years. Pritchard (1952) has developed a general theory of the structure and circulation of two-layered estuaries. Ketchum (1951) has devised an empirical method of predicting distribution of salinity and other conservative properties in a tidal estuary. He examined three different estuaries on the basis of this method and found good agreement between calculated and observed distributions. On the basis of this same method, Ketchum (1954) in a later paper shows how a plankton population is maintained in an estuary.

In Australia Rochford (1951) has proposed a scheme for the zonation of estuaries on the basis of the distribution of hydrological properties of the water and chemical properties of the bottom sediments. Using this zonation he has developed a classification system for estuaries. All of these investigations make clear the variety of hydrographic conditions which can be encountered in an estuarine situation.

THE GEORGIA SEA ISLANDS

The entire region of the Georgia Sea Islands may be described as estuarine in character. However the morphometry of the area makes

[1] Contribution No. 1 from the Marine Biology Laboratory, University of Georgia, Sapelo Island, Georgia. This research was supported by funds from the Georgia Agricultural and Forestry Research Foundation.

it unique in many respects. Along the coast is a 5 to 7 mile wide strip of salt marsh which is divided into numerous small marsh islands by a maze of creeks, channels and dead tidal rivers. Along the seaward edge of this marsh area are located the Georgia Sea Islands which serve as a barrier to destructive wave action. The tide range in this region is relatively large (6 to 10 feet). As a result, there is a semidiurnal flooding and draining of very large areas by the rise and fall of the tide. Freshwater sources are continental and coastal rivers which enter the region through a network of small rivers and creeks. Two or three sounds along 30 to 40 miles of coastline may receive direct contributions from the same fresh water river. All the rivers and sounds are interconnected by the inland waterway and many smaller channels. In this way the estuarine character of the region is established; yet the pattern of circulation cannot be treated by any of the methods thus far proposed.

It is the purpose of this paper to examine in detail a very small unit of the region described above. Certain features of the circulation of this unit are thought to be typical of the entire Georgia Coast.

Physical Description of the Duplin River

The Duplin River is a tidal river located entirely within Sapelo Island, Georgia. Having no significant fresh water source, it is, in a strict sense, an elongated tidal bay. However its quasi-dendritic tributary pattern is more suggestive of a river (Fig. 1), and it will be so treated in this paper.

The river is 9.44 kilometers in length and at mean low water (MLW) has an area of 1.66×10^6 m^2. Its "watershed" (tidal drainage area) is predominantly salt marsh with occasional wooded islands called hammocks rising above the highest tides.

A profile of the channel is shown in longitudinal section in Figure 2. Two of the three deep points, 9 meters or more in depth, are associated with sharp bends, and the other is located where the largest tributary enters the main stream. The bottom of these holes is hard, coarse sand indicating that these deep spots are probably the result of scouring by high velocity currents and turbulence near the bottom.

Although it is not the purpose of this report to describe the morphology and ecology of the salt marsh a brief account of the general features is necessary to properly demonstrate the relation of the marsh to the hydrography of the river. With the exception of a few hammocks the entire shoreline of the river is salt marsh. A typical cross

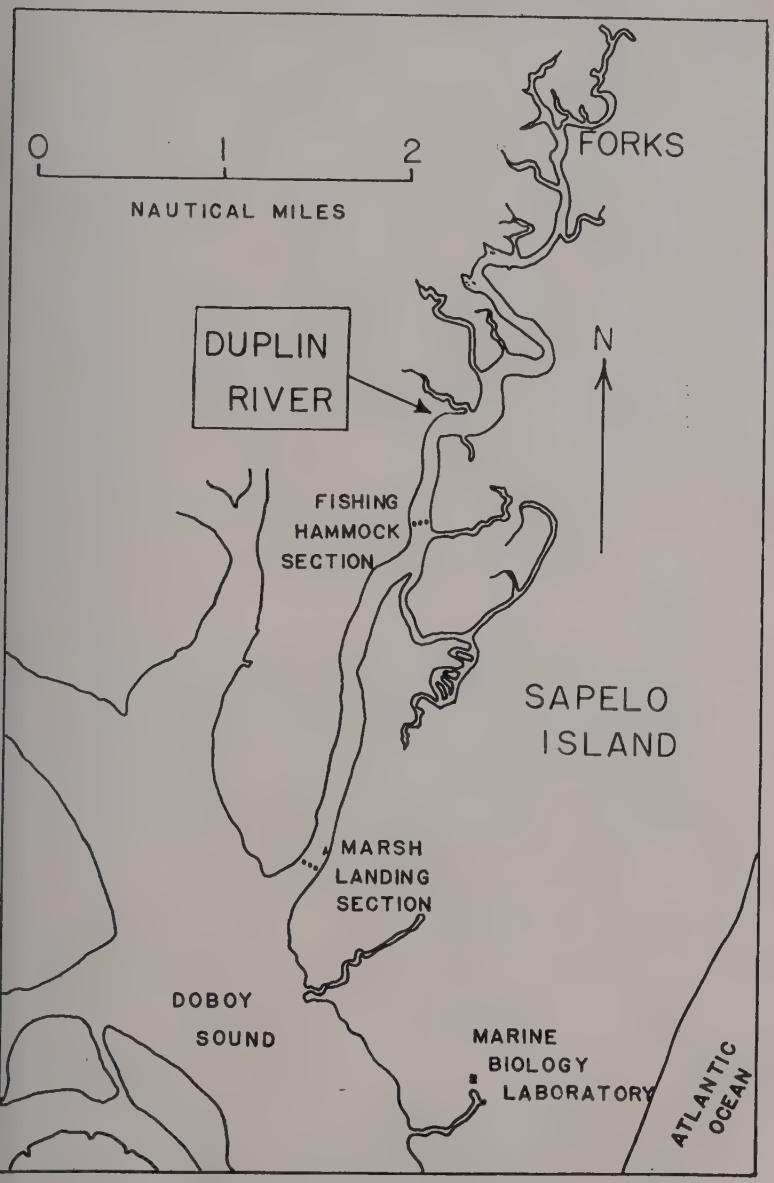

FIGURE 1. Map of Duplin River area.

section of the marshy shoreline is as follows. There is a bank zone from low tide to approximately mid-tide level where no marsh grass (*Spartina alterniflora,* Loisel) grows. This zone is covered by oysters throughout much of the downstream third of the river. Upstream from this stretch the bank zone is mostly bare mud. The slope angle of this bank is 4° where there is only soft mud and 8° to 9° where there is a shell surface or a shell layer immediately beneath the soft mud. Above the bare part of the bank marsh grass grows profusely. The slope varies from 4° to 8° through this growth up to a level slightly below high tide during neap tides. At this point there is a vertical bank 40 to 50 cm high. Field observations indicate that this vertical bank is caused by the caving of the marsh itself under the influence of heavy rains. Very high tides seem to have little effect in this respect. The vertical nature of this bank is maintained by the binding action of the root system of the marsh grass. Beyond this point is a nearly level plain where the dwarf form of the same species of marsh grass (*S. alterniflora*) is practically the only rooted plant. Much of this level plain is flooded by spring tides, but very little of it is flooded by neap tides. Throughout the marsh plain is a much

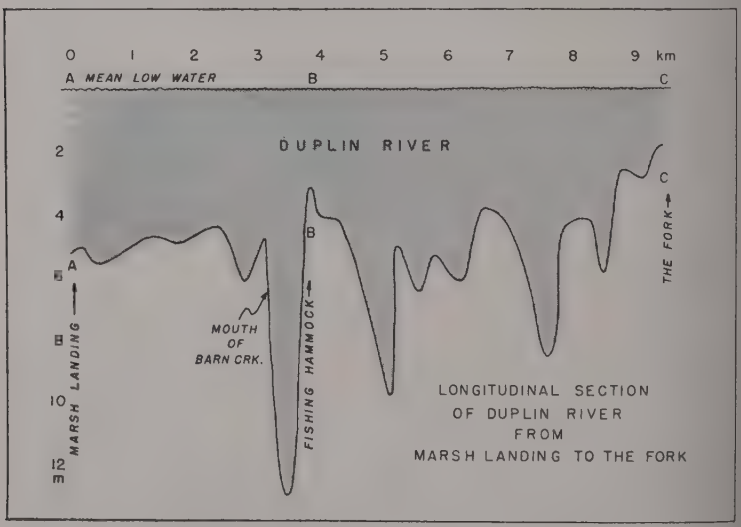

FIGURE 2. Longitudinal section of Duplin River.

branched system of small channels which serve to drain the flooded areas during the falling tide. There are no pannes or potholes as in the New England marshes (Miller and Egler, 1950).

Tides

Tide range at Sapelo Island varies from 4.5 feet to 10.5 feet with a mean range of 6.8 feet and a mean spring range of 8.0 feet (U. S. Dept. of Commerce, 1954). The tide is semidiurnal in character. All data of this report are referred to tide curves obtained with a staff gauge near the mouth of the river at Marsh Landing (Fig. 1). A delay of 24 to 27 minutes for both high and low water is observed between the official Savannah River Entrance tides and Marsh Landing. Tide ranges appear to be about the same although wind effects are so common that this cannot be stated with certainty. The level of mean low water was estimated by comparing the official

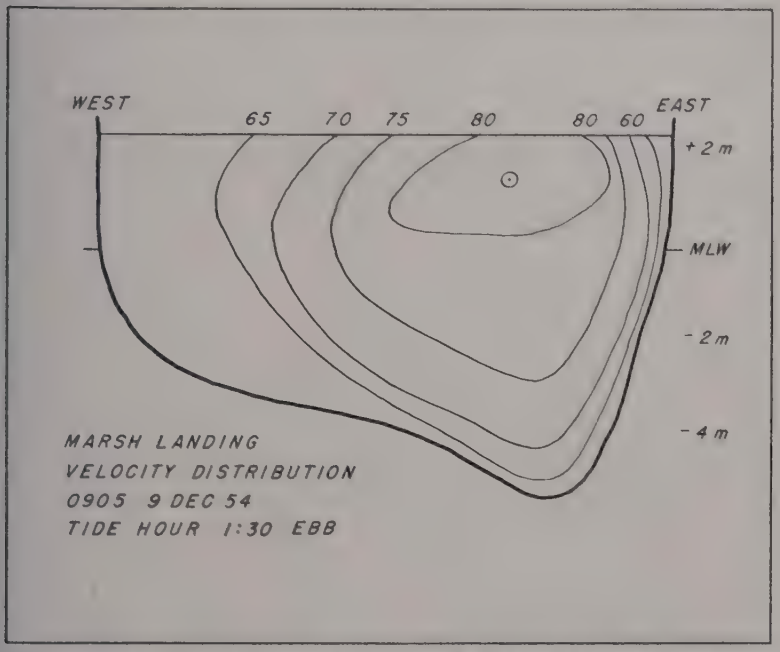

Figure 3. Typical velocity distribution at Marsh Landing during ebbing tide, cm./sec.

tide table data with field observations of the levels of several low tides. The zero level obtained is considered henceforth as mean low water.

Tidal Currents

All current measurements were made by the confined drag method (Pritchard, 1951). At cross sections near the mouth of the Duplin River and at Fishing Hammock the pattern of flow was investigated and the total transport of water measured. As the widths of the river at these points are only 240 and 215 meters with a maximum depth at mean low tide of 5 meters, three stations provided adequate coverage for obtaining the current distribution. Currents were measured at one meter intervals of depth or less at each station. The three stations could be covered in about 15 minutes; therefore the resulting current profile is essentially synoptic.

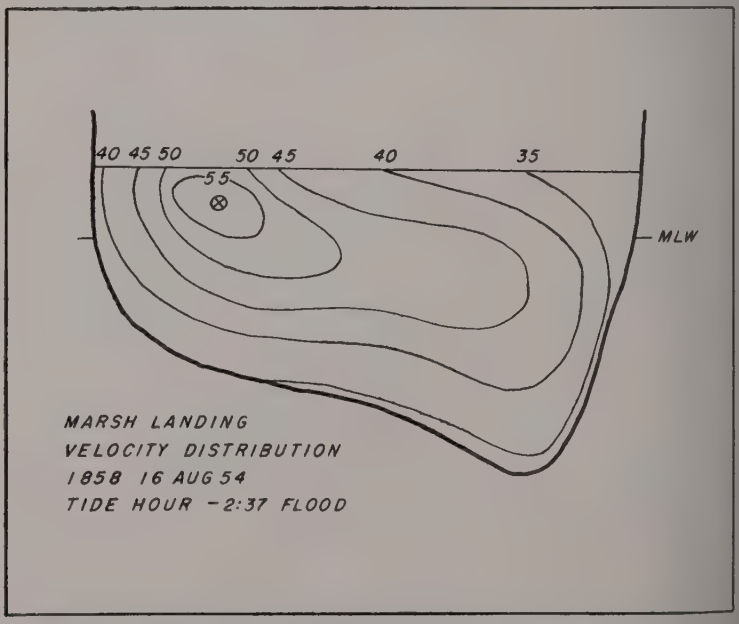

Figure 4. Typical velocity distribution at Marsh Landing during flooding tide, cm./sec.

Owing to the absence of a fresh water source two-layered flow is not a characteristic of this river. Instead, the flow pattern exhibits a core of high velocity with decreasing velocities on both sides and above and below this core. This is shown in the typical current profiles in Figures 3, 4, and 5. At Marsh Landing the high velocity core is always observed to be on the left side of the river when facing down current. At the Fishing Hammock section the flow tends to be more symmetrical (Fig. 5). Although it might be expected that the highest velocities would be on the right side because of Coriolis force, the fact that the Duplin River is not a straight channel is probably more important. Bends in the river cause meanders in the current which may persist for a considerable distance down current from the bends.

Near the times of slack water the tidal current at Marsh Landing first changes direction on the right side (side away from the high velocity core) leading to a temporary situation where the current

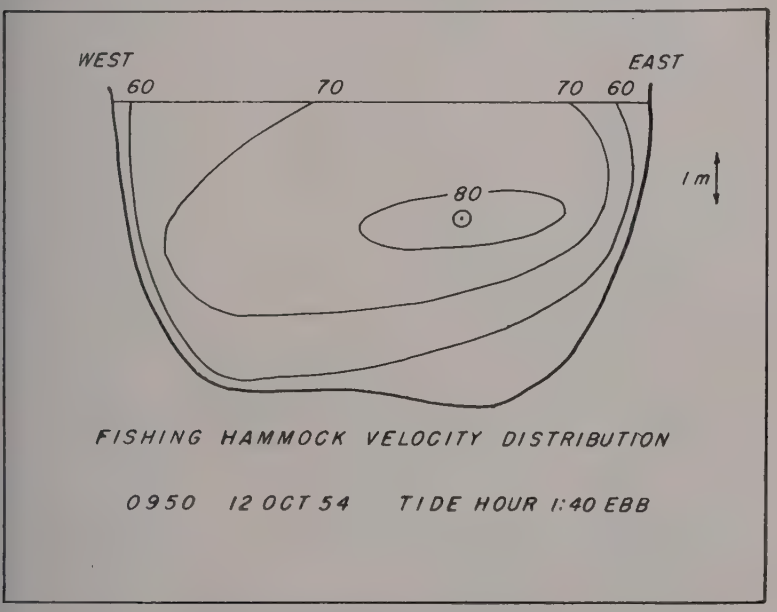

FIGURE 5. Typical velocity distribution at Fishing Hammock during ebbing tide, cm./sec.

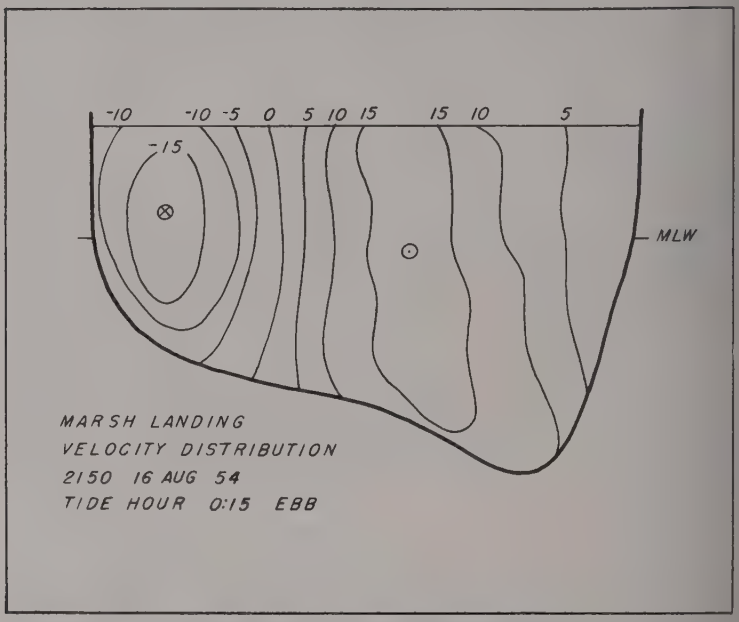

FIGURE 6. Velocity distribution at Marsh Landing at high water, cm./sec.

flows in opposite directions on the two sides of the river. An example of this is shown in Figure 6.

The mean velocity ($\bar{v}$) of the water at a specific time is obtained from the velocity profile by determining the areas between the isovels and multiplying them by the average value of the two bounding isovels. The sum of these values is then divided by the total area of the cross section giving a weighted average velocity. Plotting against time one obtains the mean tidal current curve (Figs. 7 and 8)

TRANSPORT

Transport rate is equal to the mean velocity ($\bar{v}$) times the cross-sectional area. As this area changes with the tide, all transport calculations are referred to the tide height at the time of the current measurements. To obtain the total transport during a tidal cycle the transport rates are plotted against time and the area under the curve determined by planimeter (Figs. 7 and 8). The transport curves for the flood and ebb tides are quite different in shape. During

the flooding tide transport rises rapidly, levels off, then rises again to a peak and finally drops very rapidly to zero. During the ebbing tide the pattern is somewhat different. There is a very rapid increase to a peak followed by a moderately fast drop and finally a gradual approach to zero. Maximum rate of transport occurs about 2 hours before or after high water for either flood or ebb. However transport rate reaches a higher maximum during the ebb than during the flood. This is probably due to the friction of the flooded marsh which tends to hold back the water thus setting up a steeper slope of the water surface. At this time very high velocities occur, and as a large cross-sectional area is available, high transport rates also occur.

Analysis of Transport Data

In order to properly analyze the transport values and their relationship to the tide, the nature of the drainage area must be considered. At mean low water the river has a relatively small horizontal area

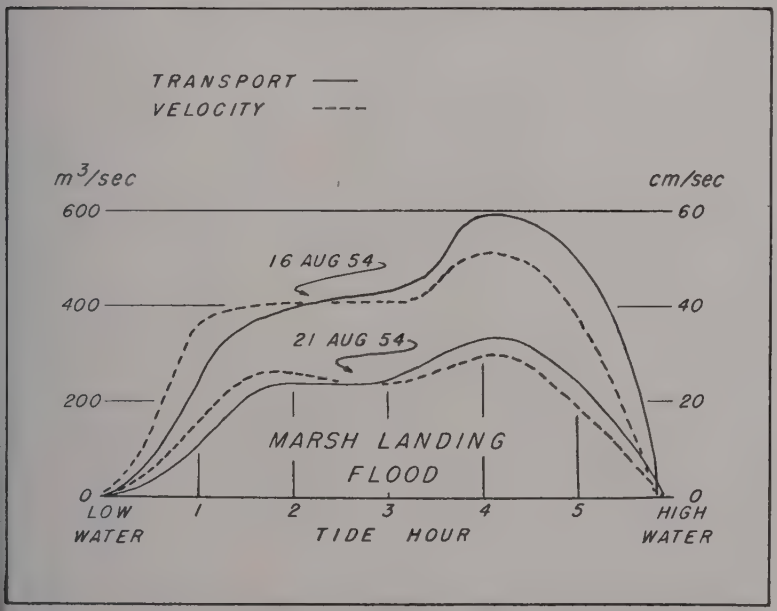

Figure 7. Representative curves for mean tidal current ($\bar{v}$) and transport at Marsh Landing during flooding tide.

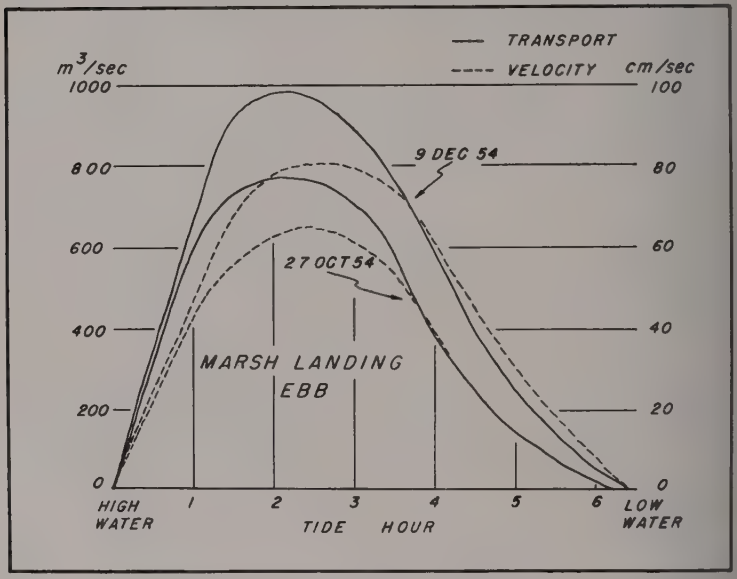

FIGURE 8. Representative curves for mean tidal current ($\bar{v}$) and transport at Marsh Landing during ebbing tide.

(1.66×10^6 m^2). The product of this area times the tide range yields a potential transport value for the river alone. The transport values obtained by field measurements far exceed these products.

A summary of the transport data together with the corresponding tide data (Table 1) shows that the transport is not related to tide

TABLE 1.
Summary of Transport Data and Corresponding Tides

Date 1954	Station	Direction	Tide range (cm.)	Height of high water (cm.)	Transport x 10-6m³ Total	Remaining in river	Leaving river
16 Aug.	M.L.	Ebb	266	238	8.73	4.42	4.31
16 Aug.	M.L.	Flood	267	240	7.13	4.44	2.69
21 Aug.	M.L.	Flood	176	202	4.25	2.93	1.32
31 Aug.	M.L.	Ebb	215	247	7.71	3.57	4.14
12 Oct.	M.L.	Ebb	323	292	18.10	5.37	12.73
12 Oct.	F.H.	Ebb	300	278	8.60	-	-
27 Oct.	M.L.	Ebb	214	249	9.41	3.55	5.86
27 Oct.	F.H.	Ebb	214	249	5.71	-	-
9 Dec.	M.L.	Ebb	301	280	12.00	5.00	7.00

range alone nor to the height of high water alone. Both variables are operative, but in differing proportions depending on the stage of the tide. To simplify this complex relationship an idealized model has been postulated. This model also forms a basis for the determination of transport values from tide data alone.

Consider the river as a uniform channel with a rectangular cross section and a surface area of 1.66×10^6 m^2. Let the flooded portion of the marsh be represented as two prisms with triangular cross section, one on each side of the river. The hypotenuses of these cross sections join the river channel at the level of mean low water (Fig. 9).

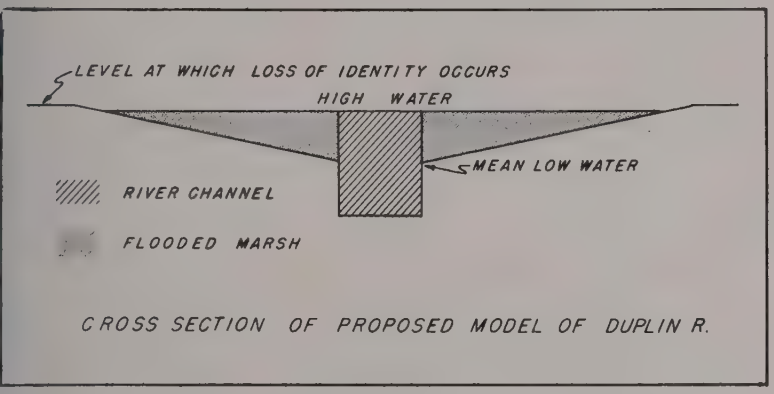
LEVEL AT WHICH LOSS OF IDENTITY OCCURS
HIGH WATER
MEAN LOW WATER
RIVER CHANNEL
FLOODED MARSH
CROSS SECTION OF PROPOSED MODEL OF DUPLIN R.

FIGURE 9. Idealized model of Duplin River.

With the aid of this model it is seen that the water passing the Marsh Landing section during a rising tide may be divided into two components—water which remains in the river and water which leaves the river and enters the marshes. The volume of water remaining in the river is equal to the river area times the tide range. However the amount of water leaving the river is a function of the level of high water and the slope of the marsh. As the volume of water leaving the river can be determined by difference (total transport—water remaining in the river), the hypothetical area flooded can be computed as follows:

Let T_{ML} = total volume transport per tidal cycle at Marsh Landing

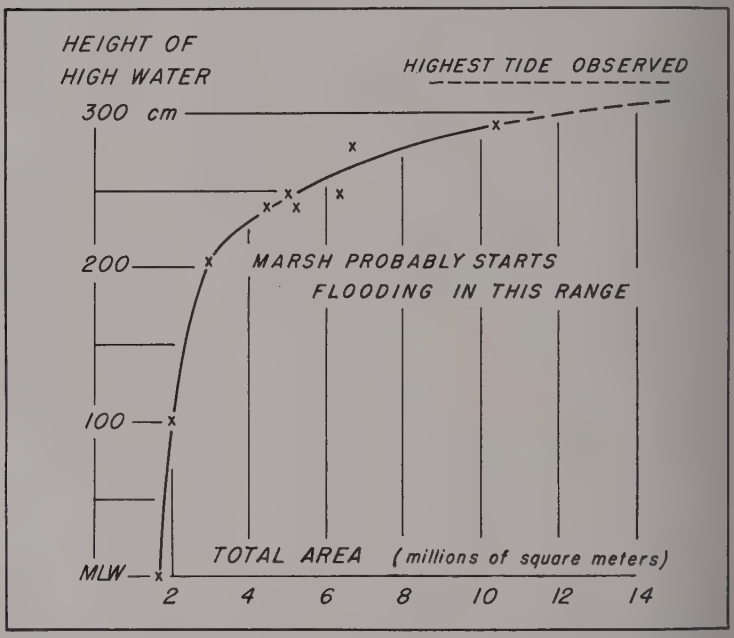

FIGURE 10. Relationship between total area flooded in the Duplin River drainage system and the height of high water.

T_{Ri} = volume remaining in the river
T_{Ma} = volume leaving the river and flooding the marsh
A_{Ri} = area of river
A_{Ma} = area of marsh flooded
HW = level of high tide above MLW
TR = tide range

Then $T_{Ri} = A_{Ri} \bullet TR$

$$T_{Ma} = T_{ML} - T_{Ri}$$

$$A_{Ma} = 2 \frac{T_{Ma}}{HW} \qquad (1)$$

Doubling the area expression is necessary in order to take into account the prism shape of the flooded marsh.

It must be emphasized here that the model is designed primarily

as a system which would behave "volumetrically" in a manner similar to the river-marsh system. There is no intent to duplicate actual morphological details of the area. Therefore the calculated area flooded is not necessarily equal to the actual area flooded. However, for purposes of computation this inequality is unimportant. In the following discussion the calculated area flooded will be considered as the area of the marsh flooded.

On the basis of the model it is now possible to formalize the relationship between actual transport values and the tide height and range. By adding the area of the river alone to the flooded area of the marsh, the total area of the water surface at high tide is obtained. Total area flooded is then plotted against the height of high water. On the same graph a point is entered for the area of the river at mean low water as determined from U. S. C. and G. S. chart No. 574. A second point for the total area at a tide level of one meter above MLW is determined by direct calculation from the average slope of the bank (6°). All other points are located by the procedure outlined above. A smooth curve was drawn which best fits the plotted points (Fig. 10).

Now although an artificial model was used as a framework for constructing this curve, actual transport data are used in locating the points. Thus the curve is a valid tool for investigating the flooding characteristics of the river-marsh system.

It is clear from this curve that above two meters (letting MLW=0) the area of the marsh flooded increases very rapidly. It also appears that at some high tide level greater than three meters the curve flattens out and the area flooded approaches infinity. Higher than normal water levels at Sapelo Island are always associated with prolonged northeast winds. This is undoubtedly a wind set-up which tends to be accentuated by the shallowness of the coastal waters in this region. On November 11, 1954 a strong northeast wind coupled with a very high spring tide produced a high water level of 320 centimeters. At this time the marshes were completely inundated and the Duplin River ceased to be a discreet drainage system. The area flooded was unbounded and, for all practical purposes, approached infinite dimensions.

An important use of the curve in Figure 10 is the determination of transport values from tide data alone. This is done as follows. For the height of high water observed read the corresponding total area flooded. Subtract from this 1.66×10^6 m^2, the area of the river

alone, thus obtaining the area of the marsh flooded. By equation (1) obtain the volume of water entering the marsh (T_{Ma}). The amount of water remaining in the river is equal to the product of the tide range times 1.66 x 10^6 m^2. Summing these two volumes gives the total transport for that particular tide. To demonstrate the use of the curve and the errors to be expected, the transport is calculated for the days when field measurements were made and the pairs of transport values compared (Table 2).

TABLE 2.
Comparison of Calculated and Observed Transport Values

Date	Transport at Marsh Landing x $10^{-6}m^3$	
	Calculated from curve in Fig. 10	Observed
16 Aug.	7.92	8.73
16 Aug.	7.96	7.13
21 Aug.	4.25	4.25
31 Aug.	7.71	7.71
12 Oct.	18.10	18.10
27 Oct.	8.21	9.41
9 Dec.	14.16	12.00

Tidal Excursion

It is desirable from the point of view of biological studies on a tidal system such as the Duplin River to know how far a parcel of water travels during one-half tidal cycle. This distance will be known as the tidal excursion.

Tidal excursion can be determined theoretically from continuity considerations using the model described in the last section as a basis. Transport measurements during the same tidal cycle at two cross sections a known distance apart are required. These will be known as the control stations. Also the mean cross-sectional area of the river between these two stations at mean low water must be estimated.

Let T_{FH} = volume transport per tidal cycle at Fishing Hammock

$\bar{a}$ = mean cross section of the river between Marsh Landing and Fishing Hammock at mean low water

Δa = change in effective cross section between Marsh Landing and Fishing Hammock from mean low water to high water

L = distance between Marsh Landing and Fishing Hammock (control stations)
l_1 = tidal excursion from Marsh Landing.

As the transport past the two control stations is not the same during the same tidal cycle, there must be some storage at high water between the two stations. This high water storage can be expressed as the difference between the two transport values,

$$\text{high water storage} = T_{ML} - T_{FH}.$$

By means of simple geometry this storage can also be expressed as

$$\text{storage} = L \cdot \Delta a.$$

Therefore

$$\Delta a = \frac{T_{ML} - T_{FH}}{L} \tag{2}$$

The value of $\bar{a}$ between the two control stations was estimated by averaging the area of six cross sections, each of which was carefully determined by sounding. Although both $\bar{a}$ and Δa were obtained for the stretch of river between the control stations (L), the general homogeneity of the river-marsh system permits use of these values a short distance above or below the Fishing Hammock station.

Of the water passing Marsh Landing (T_{ML}) part enters the watershed as storage and the remainder advances upstream through the regular river channel a distance equal to the tidal excursion. Taking the values of $\bar{a}$ and Δa as valid over the distance of the tidal excursion, the storage for this distance is the product of l_1 and Δa.

$$\text{Thus} \quad T_{ML} = l_1 \cdot \bar{a} + l_1 \cdot \Delta a$$

$$l_1 = \frac{T_{ML}}{\bar{a} + \Delta a} \tag{3}$$

Two determinations of the tidal excursion were made by this method (Table 3).

TABLE 3.
Tidal Excursion in the Duplin River Upstream from Marsh Landing

Date	Tide Range (cm.)	Transport x 10^{-6} m^3		L (km.)	$\bar{a}$ (m^2)	Δa (m^2)	l_1 (km.)
		Marsh Landing Fishing Hammock					
12 Oct.	323	18.10	8.60	3.2	784	2970	4.82
27 Oct.	214	9.41	5.71	3.2	784	1160	4.85
		By direct observation of free drags					4.8

From the data in Table 3 it appears that tidal excursion tends to remain more or less constant regardless of the tide range. This same conclusion can be reached by examining equation (3). Note that both T_{ML} and Δa are partial functions of the level of high water. The value of $\bar{a}$ is by definition a constant. Therefore equation (3) tends to yield a nearly constant value for l_1. For the Duplin River starting at Marsh Landing the tidal excursion (l_1) is about 4.8 kilometers.

Tidal excursion was also determined by direct means. Two free drags each at two meters' depth were released just below Marsh Landing at low water. The drags were observed continuously throughout an entire tidal cycle. At one point they caught on the bank and were immediately moved back out to midstream. Both drags traveled 4.8 kilometers upstream—a value which verifies the calculated excursion. The value for tidal excursion as determined here represents the mean distance that a parcel of water travels upstream during one-half tidal cycle disregarding mixing and differential current velocities.

General Discussion

Flooding of the marsh during higher than average tides increases by several times the area of water surface in the region between the Georgia Sea Islands and the mainland. The volume of water involved in the tidal circulation is thereby increased by 100 to 400 percent by a relatively small increase (25 to 50 percent) in the level of high water. As a result the conducting waterways—sounds, tidal rivers and creeks—are subjected to periods of great turbulence associated with increased current velocities. Mixing is very rapid, and as the waters are fairly shallow, no stratification can be long maintained under these conditions.

The biological implications of this type circulation are many. Periodic flooding of large areas of marsh must certainly lead to nutrient exchanges between water and mud. The growth of the marsh grass itself represents considerable production of biological

material. As some of the remains of this marsh grass eventually reach the waters in the form of organic detritus, its role in the metabolism of the estuarine area may be of great importance to the life therein. Turbulent flow in the waterways insures mixing and frequent re-suspension of the detrital material. High turbidity of the water due to the abundance of detritus probably leads to a decrease in photosynthetic activity in the water itself. On the other hand the shallowness of the water plus the effectiveness of the mixing may permit all phytoplankton to be exposed to the light for a sufficient period each day for net production by this group of plants to take place. These implications all bear on the general problem of biological productivity in the estuarine waters of Georgia, which is presently being studied at the Marine Biology Laboratory at Sapelo Island.

Conclusions

1. Current studies of the Duplin River show that the associated salt marshes are an integral part of the tidal circulation of the river.
2. Of the water entering the Duplin River during a rising tide from 1/3 to 2/3 leaves the river to flood the marshes.
3. The mean tidal excursion of water upstream from near the mouth of the river as determined by two separate methods is found to be 4.8 kilometers. This value remains nearly constant for all tide ranges because of the storage capacity of the marshes.
4. The biological implications of the type of circulation occurring in this region are numerous.

Acknowledgment

As is true of most undertakings in the field, this was a group project. Assisting in the current measurements were Drs. Lester V. Whitney, Donald C. Scott, Lawrence R. Pomeroy and Mr. George Shoptaw. The results of the free drag experiment were generously supplied by Dr. Pomeroy.

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A NEW GENUS AND SPECIES OF WHALE-LOUSE (AMPHIPODA: CYAMIDAE) FROM THE FALSE KILLER WHALE[1]

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ABSTRACT

Syncyamus pseudorcae, taken from *Pseudorca crassidens* in the Gulf of Mexico, appears to be the most specialized cyamid yet discovered. It is characterized by reduction and fusion of the mouthparts and by dorsal fusion of pereion 6 and 7. *Isocyamus delphinii* (Guérin) is reported from the same host.

INTRODUCTION

Twenty-six specimens of the cyamid described in this paper were taken from the surface of a false killer whale, *Pseudorca crassidens* (Owen), captured April 30, 1955, at station 1298 (26°30′N, 89°15′ W) in the Gulf of Mexico during a cruise of the U. S. Fish and Wildlife motor vessel OREGON. Its combination of characters sets it apart from the four genera now recognized; accordingly a new genus is established for it.

Thanks are due to Mr. Harvey R. Bullis, of the U. S. Fish and Wildlife Service, who forwarded the specimens to the U. S. National Museum.

Syncyamus new genus

Pereiopod 2 larger than pereiopod 1. Antenna 2, 2-segmented. Maxilla 2 without outer lobes. Maxilliped reduced to a simple flap. Unguis not distinct from dactyl in pereiopod 1. Gills simple. Accessory gills present in male. Pereion somites 6 and 7 fused. Type species, *Syncyamus pseudorcae,* new species.

Syncyamus pseudorcae, new species

Body greatly flattened; length about twice the greatest width. Head (including coalesced pereion somite 1) about as long as wide; sides rounded and diverging. Antero-lateral margins of pereion somite 2 produced anteriad into double lobes. Somites 3 and 4 progressively shorter and wider than somite 2; proximal portions of gills visible from above along lateral margins. Somites 5 and 6 about equally

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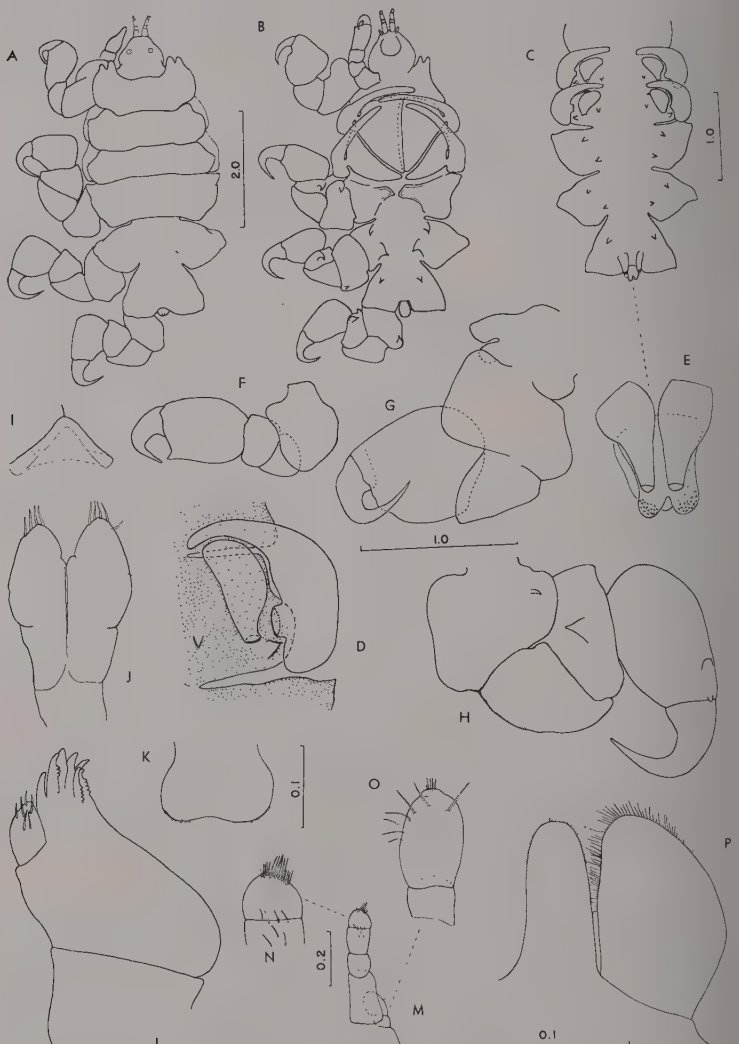

FIGURE 1. *Syncyamus pseudorcae,* new species

A. Female, dorsal; B. Female, ventral; C. Male, ventral; D. Pereion somite 4, male, ventral; E. Pleon and penis, male, ventral; F. Pereiopod 1, female; G. Pereiopod 2, female; H. Pereiopod 5, female; I. Maxilliped, female; J. Maxilla 2, female; K. Labrum, female; L. Maxilla 1, female; M. Antennae 1 and 2, female; N. Apex of antenna 1, female; O. Apex of antenna 2, female; P. Labium, female, only one outer lobe shown. Scales in mm, same for A and B; F, G, and H; I, J, L, and P.

wide, wider than the other somites; somite 5 about as long as somite 2, lateral margins converging posteriad. Somites 6 and 7 fused dorsally; somite 7 wedge-shaped, with a median concavity in posterior margin. Both males and females with two pairs of pointed tubercles on ventral surface of somite 6, one pair on somite 7. Somite 5 in the male with two pairs of tubercles, in the female with a pair of genital valves but no tubercles. Somites 3 and 4 in the male with two pairs of pointed tubercles, one pair at the base of the gills, the other pair medial to the accessory gills. Female without tubercles on somites 3 and 4.

Antenna 1 very short, about equal to the distance from the eyes to the anterior margin of the head; second and fourth segments very short, about as long as broad; fourth segment with a group of closely packed setae at the apex. Antenna 2 about 2/3 as long as first segment of antenna 1, 2-segmented. Distal segment more than twice as long as proximal segment, armed at the tip with a group of short setae and on the surface with a few longer setae.

Labrum with a shallow median invagination; antero-lateral margins rounded and clothed with fine setae. Left mandible with two incisor processes, the inner with 5 teeth, the outer with 6 teeth. Incisor process of right mandible with 7 teeth. Medial lobes of labium fused; densely covered on anterior surface with short setae; margins entire. Outer lobes rounded, bearing longer setae on distal and inner margins. Outer lobes of maxilla 1 with 7 stout setae, some with crenate concave margins. Palp one-segmented, bearing a few short setae. Maxilla 2 composed of a single lobe bearing 4-5 slender setae at the distal end. Right and left maxillae 2 fused along their medial margins. Maxilliped reduced to a small triangular flap, in very young as well as in adult specimens.

Pereiopod 1, 5-segmented; first segment (basis + ischium) nearly as broad as long; propodus about 4/5 as wide as long, palmar margin transverse, defined by a tooth. Pereiopod 2, 4-segmented, basal segment about twice as broad as long, produced anteriad into a broad quadrate process; propodus a little longer than broad; dactyl strongly curved, closing on medial surface of propodus. Pereiopods 5-7 similar, with short and wide segments; basal segment, carpus and propodus each with a recurved spine on the medial surface.

Gills larger in females than in males; proximal parts carried along the lateral margins of pereion somites 3 and 4; distal parts more slender, curved in under the pereion. Oostegites subtriangular. Ac-

cessory gills in male well developed, sausage-shaped, arising near the points of origin of the gills.

Pleon simple in female, in male provided ventrally with a bilobed appendage bearing minute setae on the sculptured tips.

Length, from anterior margin of head to tip of pleon: females with embryos, 4.0-4.9 mm, average of 7 females, 4.5 mm; 3 adult males, 3.3, 3.7, and 4.0 mm.

Types. Deposited in the U. S. National Museum: Holotype, female with embryos, 4.8 mm in length, Cat. No. 98121; allotype, adult male, 4.0 mm in length, Cat. No. 98122; paratypes, 3 males and 21 females, Cat. No. 98123.

Remarks. Table 1 summarizes the distinctive features of the five currently recognized genera of Cyamidae, including the one proposed in this paper. *Paracyamus* G. O. Sars is not included, since Margolis (1955) has demonstrated that the only character which separated it from *Cyamus,* the absence of maxillipedal palps in the adult, varies among the individuals of certain species. Adult specimens of *C. erraticus* Roussel de Vauzème (syn. *Paracyamus erraticus*) and *C. catadontis* Margolis were found with completely developed palps, with one palp lacking, and with both palps lacking. As these two species are thus intermediate between *Cyamus* and *Paracyamus.* Margolis considers *Paracyamus* a junior synonym of the older genus *Cyamus.*

It is of interest to note that at present all the genera except *Cyamus* are monotypic.

There is reason to believe that *Syncyamus* is the most specialized cyamid yet discovered. The extreme reduction of the maxilliped, the reduced and medially fused maxillae 1, the fused inner lobes of the labium, and the very short antennae 1 and 2 lend support to this belief. The dorsal fusion of pereion somites 6 and 7 is also a specialized character.

In addition to the specimens of *Syncyamus,* a number of specimens of *Isocyamus delphinii* (Guérin) were taken from the *Pseudorca.* Insofar as I have been able to determine, there is only one previous record of *I. delphinii* from this host. It was taken from a *Pseudorca* captured by the Hirondelle II in 1911, at station 3142, near São Miguel Island, one of the Azores (Chevreux, 1913, p. 15; 1935, p. 134). This cyamid has also been found on *Delphinus delphis* Linnaeus (Lütken, 1893, p. 433, footnote), *Globicephala maelena* (Traill) (Lütken, 1873, p. 250; Chevreux, 1913, p. 15; 1935, p. 133; Stephen-

TABLE 1. Principal characters of the genera of Cyamidae.

	Type Species	Antenna 2, no. of segs.	Maxilla 2, outer lobe present?	Maxilliped, palp developed in adults?	Pereiopod 1 and 2, relative size	Pereiopod 1, unguis distinct from dactyl?	Gills	Accessory gills present in male?	Remarks
Cyamus Latreille, 1796	*Oniscus ceti* Linnaeus, 1758	4	Yes	variable	P. 2 larger	No	Single or double, straight or spirally coiled	Yes	Includes *Paracyamus* G. O. Sars
Isocyamus Gervais and Beneden, 1859	*Cyamus delphinii* Guérin, 1836	3	No	No	P. 2 larger	Yes	Single	Yes	Maxilla 1, palp 2-segmented
Platycyamus Lütken, 1873	*Cyamus thompsoni* Gosse, 1855	4	?	No	nearly equal	No	Single	Yes	Head not fused with pereion somite 1
Neocyamus Margolis, 1955	*Cyamus physeteris* Pouchet, 1888	2	No	No	P. 2 larger	Yes	fasciculate	No	
Syncyamus n. gen.	*Syncyamus pseudorcae* n. sp.	2	No	No	P. 2 larger	No	Single	Yes	Pereion somites 6-7 fused

son, 1942, p. 445), *G. scammoni* Cope (Hiro, 1938, p. 77), and *Grampus griseus* (Cuvier) (Chevreux, 1913, p. 15; 1935, p. 133).

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RED TIDE AND THE FLUCTUATION OF CONSERVATIVE CONCENTRATIONS AT AN ESTUARY MOUTH[1]

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ABSTRACT

A set of observations of the conservative concentration, salinity, at an estuary mouth in a Red Tide region is generalized by an extension of the mixing length theory of tidal flushing for steady state to one for transient state. The river flow and tidal current are taken as functions of time, but not of space. The solution confirms the expectation that the intensity of the zone of rapid transition of conservative concentrations is greatest during high river flow and low tidal ranges. The solution also indicates that the tidal advection and diffusion reinforce each other.

INTRODUCTION

Many investigators, among them Ketchum and Keen (1948) and Gunter *et al.* (148), have stressed the possible role of terrigenous nutrient supply in the blooming of Red Tide organisms. Recent studies by the Marine Laboratory and U.S.F. & W.S. have suggested the possibility that such blooms may favor waters of salinity, a conservative concentration, generally found near estuary mouths. Other investigations by the Laboratory, and in particular by Hela, have disclosed the possible importance of a "frontogenetic" zone (really, a zone of rapid transition) in initiating, facilitating or accelerating the growth of Red Tide organisms in nature. A field study of this suggestion was carried out by Hela at the mouths of the Boca Grande and San Carlos Bay and his findings are reported elsewhere (Hela, 1954). It is the primary purpose of this paper to generalize on his observation by relating the physical presence of this transition zone (already shown to be present by others) to the river and tidal stages through an extension of the mixing length theory of tidal flushing. A simplified picture of the fields of conservative concentrations, such as salinity, may then be had which will furnish a more solid foundation for the pursuit of further study of the complex Red Tide phenomenon. Among the factors neglected here is the variable boundary effects.

In estuaries where the energy of mixing is derived primarily from tidal movements, the mixing-length theory of tidal flushing (Ketchum,

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1951, Arons and Stommel, 1951) is a very attractive one as witness its success in describing the steady-state salinity distribution. The difficulty encountered with the order of magnitude of the proportionality factor B defined by the cited authors in

$$K = 2BU_oX_o \qquad (a)$$

where
- K is the eddy diffusivity
- U_o tidal current amplitude
- X_o tidal displacement amplitude

may not be fundamental, for such factors as stability, boundary roughness and frictional force were not considered; possibly B is a function of these factors. It is conceivable, for example, that

$$B = B_1B_2 \qquad (b)$$

where B_1 is a parameter summarizing the effects of roughness, friction and so on, while B_2 is the one whose magnitude was sought. The three assumptions made by these authors, and accepted in this paper, are:

a. complete vertical mixing
b. complete horizontal mixing (which implies, among other things, the negligibility of the Coriolis force, non-existence of tranverse advection and diffusion)
c. the eddy diffusivity is directly proportional to the product of excursion and speed of the tidal stream.

In the present paper the local time change of salinity in a fixed volume is set equal to the sum of tidal diffusion and advection due to tidal current and river flow. The river flow is assumed to vary sinusoidally with a period very much larger than that of the tide, so that over a tidal period the river flow is substantially constant and the time change of salinity is due primarily to tidal characteristics.

The zone of interest is confined to within a few miles of the estuary mouth and hence within that zone the tidal current is relatively constant; on first approximation, it is assumed constant. In view of assumption (c) above, this is equivalent to a spatially constant eddy diffusivity in the zone of interest.

Kinematics of the Model

The x-axis is directed positive downstream with the origin, O, at x_o distance upstream from the estuary mouth; the zone of interest is in-

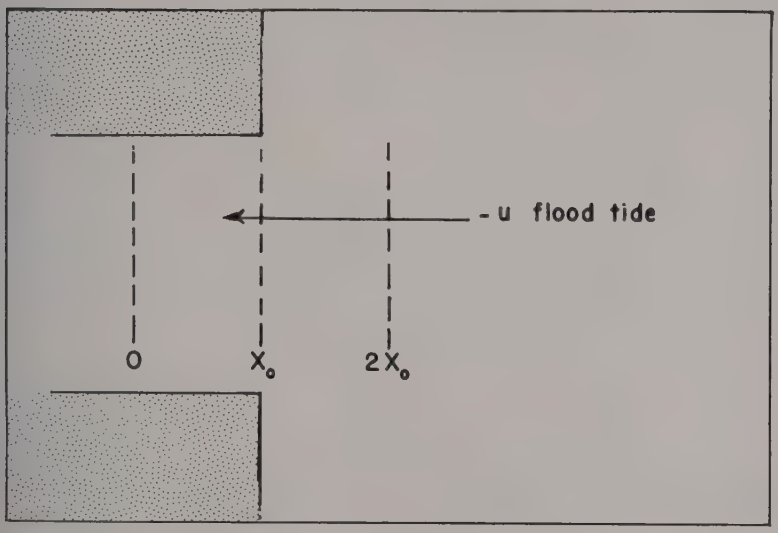

FIGURE 1. A schematic estuary mouth.

cluded in the approximate range of O to $2x_o$, where x_o is the tidal excursion (see Figure 1). The incoming tide is parallel to the x-axis and is directed toward the origin, hence its velocity is -u. On the ebb tide its velocity is u. The tidal current is taken as

$$u = u_o \sin(Wt) = u_o \cos(Wt - \pi/2) \tag{1}$$

where the amplitude u_o is constant, W is $2\pi/T$, T is the tidal period and t is time. The tidal excursion of the water particles in one-half tidal period is, from (1):

$$x_o = u_o \int_o^{T/2} \cos(Wt - \pi/2)\,dt = 2u_o/W \tag{2}$$

The river flow, u_1, is approximated by

$$u_1 = b \cos(2\pi t/T_1) \tag{3}$$

where b is a constant and the range of t is confined to greater than $-(T_1/4)$ and less than $+(T_1/4)$.

It is to be noted that the ambient current and eddy diffusion perpendicular to the x-axis between the interval of $x_o - 2x_o$ are assumed negligible.

By (c) above the eddy diffusivity, K, is

$$K = B_3 x_o u \tag{4}$$

where B_3 is a non-dimensional constant identical in nature to that of Arons and Stommel but may not be of the same magnitude. For convenience, B_3 will henceforth be written as B.

The Equation of Salt Transfer

The equation governing the salinity distribution is

$$\partial s/\partial t + (u_1+u)\,(\partial s/\partial x) = \partial/\partial x(K\partial s/\partial x) \tag{5}$$

where s is the observed salinity at any point x; other notations have their usual meaning. When (1) and (3) are substituted in (4), one has, after some transposing:

$$\frac{1}{u_o \cos(Wt-\pi/2)}\left[\!\left[\frac{\partial s}{\partial t} + u_1 \frac{\partial s}{\partial x} \right]\!\right] = -\frac{\partial s}{\partial x} + Bx_o \frac{\partial^2 s}{\partial x^2} \tag{6}$$

A solution of (6) in the following form is sought:

$$s = Me^{-mx} + S_o \tag{7}$$

where M is a sole function of time, t, and m is a positive constant and S_o is a constant salinity. Substitution of (7) in (6) gives, after cancelling the common exponential factor, e^{-mx}, and some transposing:

$$(1/M)dM/dt = u_1 m + m(1+Bx_o m)u_o \cos(Wt-\pi/2) \tag{8}$$

The integration of (8) yields, after the substitution of (3) for u_1,

$$M = Ae^{(T_1 bm/2\pi)\sin(2\pi t/T_1) + (m/W)\,(1+Bx_o m)u_o \sin(Wt-\pi/2)} \tag{9}$$

where A is an integration constant.

Substitution of (9) in (7) gives the desired solution to the equation of salt transfer (5).

Application of the Solution to San Carlos Bay Estuary

For T_1 very much larger than T, that is,

$$T_1 >> T \tag{10}$$

and for time, t, the order of magnitude of T, the exponential in equation (9) with the factor $(T_1 bm/2\pi)$, changes very little and may be considered constant for the time being and absorbed in the coefficient A in (9). The constant m in (9) and (7) is taken as a multiple of b/K, where b and K are defined respectively in equations (3) and (4):

$$m = cb/K = cb/2Bx_o u_o = a/Bx_o \tag{11}$$

where $a = cb/2u_o$ is a positive constant. The equality in (11) is based on the consideration (Arons and Stommel) that when K is large the transitional zone, represented by the exponential factor in (7), is weak and when b is large it is more intense. Considering (2) and (11) the coefficient of $\sin(Wt-\pi/2)$ in (9) reduces to

$$u_o(m/W)\ (+Bx_o m) = a(1+a)/2B \tag{12}$$

And hence the solution to (5) is

$$s = Ae^{-(ax/Bx_o)} + [a(1+a)/2B] \sin\ (Wt-\pi/2) + S_o \tag{13}$$

The San Carlos Bay estuary is located on the west coast of Florida. The Caloosahatchee River, forming the upper portion of the estuary, drains into San Carlos Bay which communicates with the Gulf of Mexico primarily through its opening to the south. This opening is bounded in the east by the coast of the Florida peninsula so that, outside the estuary, water movement perpendicular to the direction of the longitudinal axis of the estuary mouth is considerably reduced. A suitable set of salinity data was collected in this estuary mouth by Dr. Ilmo Hela of this laboratory during his studies of the Red Tide phenomenon on May 28, 1954. Figure 2 shows the station locations and the topography of the surroundings. The set of salinity data collected at Boca Grande Pass is not utilized here because of the complication of a north-south current across the Pass. Nevertheless, the fundamentals given here still apply.

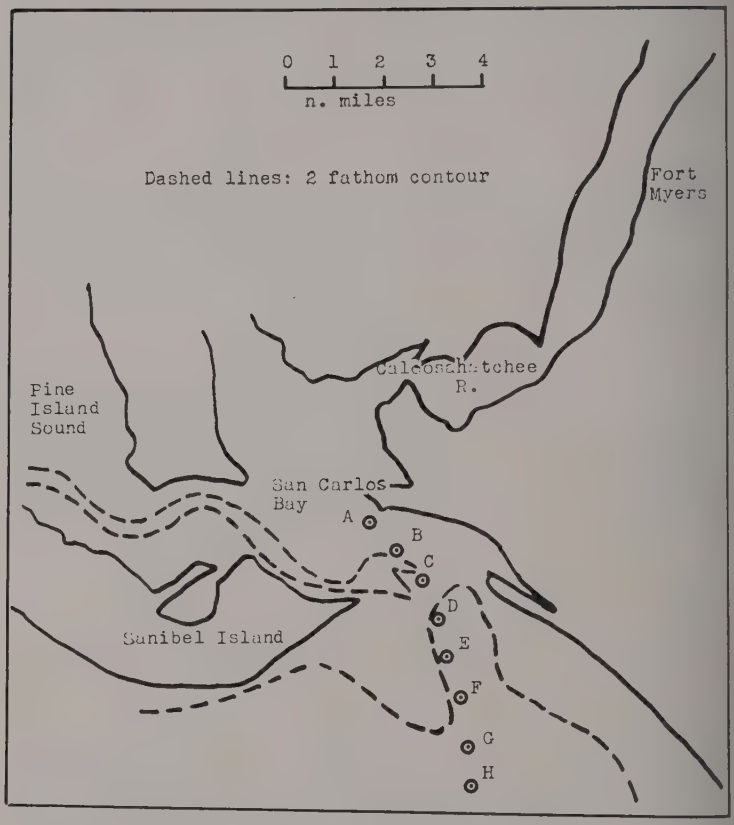

FIGURE 2. Station locations in San Carlos Bay.

The tidal period on that day was approximately 14 hours. Because of the demand of other Red Tide observations, no current measurements were made. The choice of magnitudes for the constants in equation (13) must, of necessity, be arbitrary for the present, as the available field data are not adequate for an evaluation of these constants to assure their general applicability; these magnitudes are

$$a = 1/5$$
$$B = 4/30$$

$$x_o = 2.4 \text{ n. miles}$$
$$A = -3.3 \text{ ‰}$$
$$S_o = 34.80 \text{ ‰} \qquad (14)$$

Substituting (14) in (13) one obtains

$$s = -3.3\, e^{-(.62)x} + 0.9 \sin (2\pi t/14 - \pi/2) + 34.80 \qquad (15)$$

with x in nautical miles and t in solar hours. Because of equation (1), $t = O$ corresponds to high tide as $u = O$. At $t = T/4$, $u = u_o$ corresponds to ebb strength; similarly, $t = 3T/4$ corresponds to flood strength as $u = -u_o$. In Table 1 may be found several magnitudes of the first term in (15) for chosen values of t and x.

TABLE 1
Computation of Equation (15)

Tidal phase	t (solar hours)	Station x in n. miles	A 0	B .9	C 1.7	D 2.5	E 3.3	F 4.1	G 5.3	H 5.9
high	0		1.35	.79	.46	.30	.17	.10	.05	.03
	1.4		1.58	.89	.56	.33	.20	.13	.06	.04
	2.8		2.50	1.42	.89	.53	.33	.20	.10	.07
ebb	4.2		4.31	2.47	1.52	.92	.56	.43	.17	.11
	5.6		6.82	3.90	2.37	1.45	.89	.69	.27	.17
low	7.0		8.11	4.62	2.84	1.72	1.06	.82	.30	.21
	8.4		6.82	3.90	2.37	1.45	.89	.69	.27	.17
	9.8		4.31	2.47	1.52	.92	.56	.43	.17	.11
flood	11.2		2.50	1.42	.89	.53	.33	.20	.10	.07
	12.6		1.58	.89	.56	.33	.20	.13	.06	.04
high	14.0		1.35	.79	.46	.30	.17	.10	.05	.03

With the help of Table 1, equation (15) is plotted in Figure 3. Salinity values for stations E and F were omitted to permit a clearer presentation. In an effort to reduce the gap between the vertical homogeniety assumption in equation (15) and the stratification of the actual estuary, the observed data plotted are simple averages of bottom and surface salinity values according to the equation,

$$\tfrac{1}{2}(S_1 + S_2) = S \text{ (plotted salinity)} \qquad (16)$$

where S_1 and S_2 are salinity values observed at the surface and the bottom respectively. It is seen that the general correspondence between the computed and observed is good. The observed values marked 1 and 2 in Figure 3 belong to the sets labeled C and D respectively. The large discrepancy between these values and the corresponding

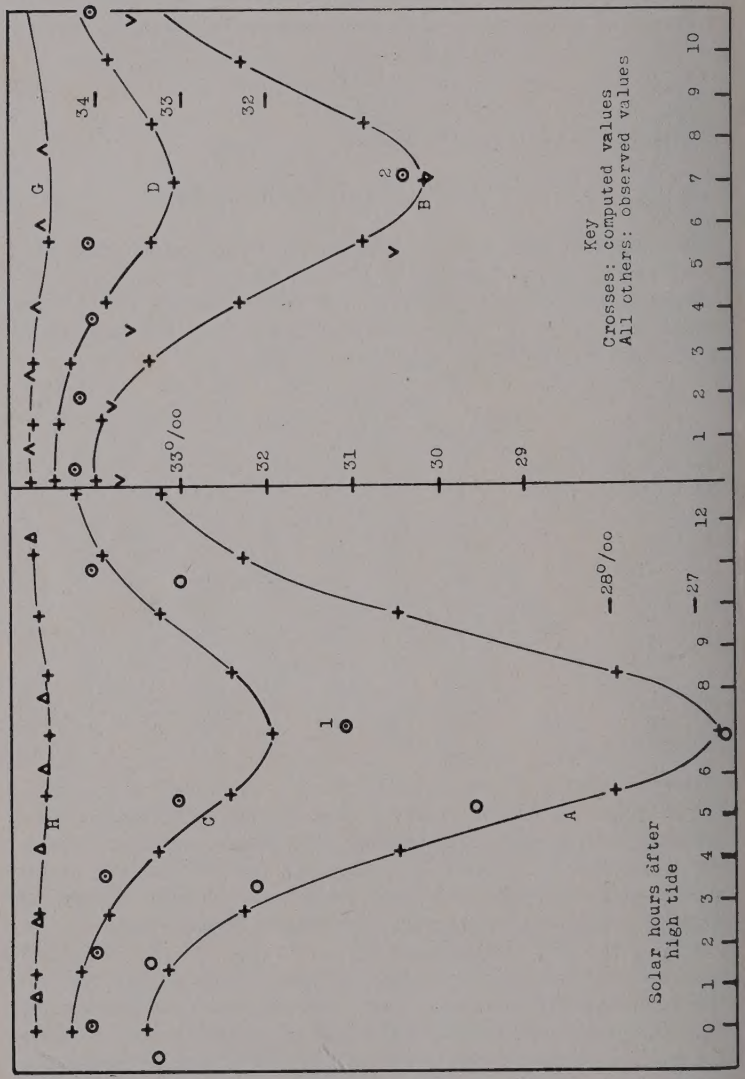

FIGURE 3. a. Computed and observed salinities for Stations A, C and H.
b. Computed and observed salinities for Stations B, D and G.

values on the theoretical curves are due in part to the inadequacy of equation (16) to approximate the vertical homogeniety requirement, and in larger part to the inflow through Estero Pass of less saline water drained from the swampland to the east. Other smaller discrepancies are explainable in terms of the lateral salinity gradient ignored in equation (15).

The effect of varying river discharge, as can be seen from equation (9), is to modulate the amplitude of the salinity fluctuation both in time and space. The greater the river discharge the more intense the transition zone, while the greater the magnitude of u_o, the less intense the transition. In other words, other factors being equal, the conditions most favorable for a strong gradient of salinity (or other conservative concentrations) at the estuary mouth is during the period when there is a combination of high river runoff and a regime of low tidal range.

Discussion and Conclusion

In the steady-state condition in an estuary, the constant salinity in a fixed unit volume is the result of the complete balance of downstream advection of salt out of the volume with the upstream eddy diffusion of salt into the volume. However, equation (15) shows that both the tidal advection and diffusion terms have the same sign and phase; that is, for example, during ebb tide both the tidal advection and eddy diffusion mechanisms act together to decrease the salinity within the fixed unit volume. This is not unexpected, considering the model employed; but it is contrary to first impression.

It has been suggested that observed Red Tide outbreaks have tended to fall near periods of spring tides. Since from equation (11) one sees that the transition zone near the estuary mouth is weak during these periods, one is led to the conclusion that an effect of spring tide on Red Tide outbreaks is due to other causes, such as stirring of the estuary bottom, than the presence of a strong, sharp transition zone at the estuary mouth.

The extension of the mixing length theory of tidal flushing to river and tidal fluctuation of conservative concentrations at an estuary mouth appears valid. A not unexpected aspect of tidal advection and diffusion is that they act in phase to reinforce each other.

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